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APPLICABILITY OF ELECTRIC PROPULSION FOR FUTURE MILITARY SATELLITES

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Office of the Assistant for Study Support
Kirtland Air Force Base, New Mexico

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The feasibility of utilizing electric propulsion subsystems to perform conventional propulsion functions in mission areas of Air Force interest is investigated. Consideration is given to using electric propulsion either alone or in conjunction with conventional propulsion subsystems. In each case, the results are compared with the conventional propulsion subsystem that otherwise would be used. The analysis identifies some areas wherein the application of electric

propulsion would result in substantial cost savings, but the study also indicates other areas in which the applications of electric propulsion is not cost effective for the missions under consideration in this study.

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propulsion would result in substantial cost savings, but the study also indicates other areas in which the applications of electric propulsion is not cost effective for the missions under consideration in this study.

SUMMARY

A survey of post-1975 satellite missions was made and composite mission models were developed for major mission areas. Since a large number of missions and satellite propulsion subsystems need to be analyzed, a computer program was developed to perform the basic analyses. The program, which was taken initially from a report of the Air Force Rocket Propulsion Laboratory, was modifed to accept more propulsion functions, different required power inputs, more sophisticated methods of determining some propulsion system parameters, and a more detailed weight analysis.

A study was made of the performance capabilities and costs of selected launch vehicles. Satellite costs were based on an analysis of the weights, power requirements and other characteristics of the major subsystems of each satellite under study. A computerized cost model was developed to estimate the nonrecurring cost and the first unit cost of each type and size of satellite. Ten-year systems cost of specified constellations of satellites were developed from the basic cost estimates after the number of satellites required in each instance was determined.

The analyses show that the use of electric propulsion to raise satellites from intermediate earth orbits to a synchronous equatorial orbit would result in transit times that are not practical from an operations point of view and would not result in cost savings. In contrast, if north-south stationkeeping is required for a satellite, use of some electric propulsion devices would make available the additional weight and volume that is required to enhance the mean mission duration (MMD) of the satellite. For example, for the hybrid mercury propulsion subsystem, the increase of satellite MMD is from 3 to 4.6 years.

This enhancement would result in an estimated cost saving of approximately 20 percent, based on a constellation of small category satellites deployed and maintained in a synchronous equatorial orbit over a period of ten years. This saving results directly from the reduced number of satellites and launch vehicles required to maintain a given capability rather than from lower unit costs. Other electric propulsion subsystems showed comparable or less savings while some subsystems showed no cost effectiveness.

FOREWORD

This report on the applicability of electric propulsion for future military satellites was performed by the Office of the Assistant for Study Support at the request of the Director of Laboratories, Hq AFSC, during the period of February 1972 to July 1973. The study supports the Air Force Rocket Propulsion Laboratory technology program. The feasibility of utilizing electric propulsion subsystems to perform conventional propulsion functions in mission areas of Air Force interest is investigated. Consideration is given to using electric propulsion either alone or in conjunction with conventional propulsion subsystems. In each case, the results are compared with the conventional propulsion subsystem that otherwise would be used.

The analysis identifies some areas wherein the application of electric propulsion would result in substantial cost savings, but the study also indicates other areas in which the applications of electric propulsion is not cost effective for the missions under consideration in this study.

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SECTION I

INTRODUCTION

The construction of post-1975 satellite mission models was based primarily on existing documentation of actual projected USAF mission requirements. The space transportation system (STS) mission model (Ref.1) provides the most comprehensive and complete listing of these missions. Two categories of missions from that model are considered applicable to this study. The first category consists of those missions which are scheduled for deployment through the mid-1980 time period. In the first category of missions a need has been established for the capability and the technology is available to design and build the satellite systems to fulfill the mission requirements. The second category of missions consists of those systems for which a viable program can be defined but for which implementation would require either significant technological or engineering advances, changes in national policy, or the emergence of new threats.

Both categories of missions form the basis of composite mission models for analysis of electric propulsion systems. In these composite mission models, three main mission areas are defined with the remaining missions classified as miscellaneous. The three main areas are geosynchronous, sun synchronous and near earth, and a composite mission is defined in each of these areas for analysis.

For this analysis, a large variety of satellite propulsion systems needs to be studied. Total propulsion system weight, propellant tank size, total impulse requirements, and many other relevant characteristics must be calculated for each propulsion system. To perform these calculations, a computer program, developed by the Rocket Propulsion Laboratory (RPL) (Ref. 2),

was adopted for use in this report. This program was expanded to include more propulsion systems and more flexibility as to their function. For example, thrust levels, total mission functions, power requirements, and other aspects of the program were expanded; while a spiraling mode, apsidal control, and nodal regression were added to the mission functions.

The program sizes, weighs, and characterizes the solar panels, centerbody, and propulsion system and calculates the total on board electric power. Some of the parameters which may be varied are the satellite life, initial gross weight, initial angular momentum, spacecraft propulsion system, and mission required power.

The practicality of employing electric propulsion to perform propulsion functions under study is appraised in terms of the cost effectiveness of the potential system compared with that of a baseline system employing conventional propulsion devices. Cost estimates used as inputs to the effectiveness analyses include all costs incident to (a) development, testing and production of the satellite and launch vehicle, (b) deployment of a constellation of satellites in the required orbit, and (c) maintenance of the constellation of satellites in orbit during a period of ten years.

SECTION II

MISSIONS

GEOSYNCHRONOUS AND 24 HOUR ELLIPTICAL ORBIT MISSIONS

The most important group of satellites to be analyzed from a mission viewpoint are those in 24 hour elliptical and geosynchronous orbits. These include a wide selection of commercial and military satellites including communication relay, navigation aids, meteorological reconnaisance, and strategic and defensive surveillance. One of the most useful satellite orbits is the geosynchronous orbit or circular orbit in the equatorial plane with an orbital period of one sidereal day. A satellite in such an orbit will remain fixed with respect to an observer on the earth. A satellite at synchronous altitude but inclined to the equatorial plane would appear to the observer on the earth as following a figure eight in the sky. In this analysis results are presented where the satellite is taken to synchronous equatorial orbit and the inclination is removed by the launch vehicle. Analyses were also made where the satellite is taken to synchronous altitude and the plane change removed by the satellite propulsion system; however the results are not practicable and are not presented. Many of the missions require close pointing accuracy and precise stationkeeping ability. Therefore, one of the parameters is the pointing accuracy of the satellite. As this accuracy is increased the propulsion requirements are increased. Any value of pointing accuracy may be used in the program; however, results are presented only for the fine mode of 0.100°.

The basic mission performance is characterized best by a 3-axis stabilized spacecraft. Much of the analysis is also applicable to spin stabilized satellites. A fully stabilized satellite presents the most demanding propulsion

requirements and offers a much higher level of on-board electric power capability with the use of one degree of freedom sun oriented solar array. This satellite does not require the rapid pulsing capability of spin-stabilized spacecraft and can thus utilize a wider range of propulsion systems. Since the basic purpose of the analysis is a comparison of the propulsion system concepts, the fully stabilized satellite is therefore considered a better concept for comparison. Separate spin-stabilized comparisons will be discussed when these comparisons are considered valid and when spin stabilization offers an alternate method of accomplishing the mission.

The missions were further subdivided into the following three categories of satellites by weight: 1,000 lb., 2,000 lb, and 3,000 lb, herein referred to as small, medium, and large category satellites. From an analysis of existing programs, typical values were determined for the important characteristics of the satellites in each category.

SECTION III

SATELLITE CHARACTERISTICS

1. SATELLITE GEOMETRY

Geometrically, the spacecraft examined in this study may assume a cylindrical, spherical, or rectangular shape; however, in every case the solar panels are a one degree of freedom articulated array which forms two rectangular panels diametrically opposed and pointed toward the sun. The three models used for the spacecraft geometry do not represent any specific design in the family of prospective geosynchronous satellites, but merely a consistent set of dimensions, weights, bulk densities, and inertias. The centerbody contains all of the remaining equipment and in the case of a reactor power supply, the centerbody would comprise the entire satellite, the solar panels being replaced by the internally mounted reactor. The general geometrical characteristics were taken from the STS mission analysis (Ref. 1); and the models appear consistent with these general data.

2. POWER

The maximum possible available on-board power is a function of the size and type of the satellite, the mission, the maximum dimensions allowed, type of power supply and many other factors. A good rule of thumb for approximating this power is the empirical formula (Ref. 2)

$$\text{Power}_{\text{possible}} = -.4 + 1.25 \left(\text{Weight}_{(\text{gross})}/1000\right) \qquad (1)$$

where Power is in kilowatts, and Weight is in pounds. This formula was used for the purpose of limiting the analysis in this report. No mission was considered which resulted in the required on-board power exceeding the $\text{Power}_{\text{possible}}$ as calculated from this formula.

The actual total power requirements for a composite mission was obtained by adding the mission power to the propulsion power. The mission power was obtained by analysing all the available satellite systems to obtain a power level consistent with the mission and the size of the satellite. For the 1000 lb. category of satellites a mission power of 520 watts was indicated while 1000 and 1440 watts were required for the 2000 lb. and 3000 lb. categories respectively

The propulsion power was calculated based upon the type of propulsion system, weight and thrust consideration. After the actual total power to be used was known, the size and weight of the power subsystem was determined. The solar panels were sized and the weight determined by utilizing an ideal specific weight, a percent life degradation factor, and a specific surface area necessary to produce a given amount of power.

SECTION IV

PROPULSION SYSTEM FUNCTIONS

1. INTRODUCTION

With the mission and the postulated space craft defined, a consistent set of maneuvers and control requirements were identified. These requirement functions are of five types:

a. Initial positioning

b. Attitude control

c. Stationkeeping

d. Repositioning

e. Orbit raising and lowering.

Initial positioning involves removing the launch vehicle injection errors to attain the desired orbital flight path. In addition, it generally requires moving the satellite from the injected in-track position to the desired in-track station location.

Attitude control involves removing the attitude errors to maintain the desired pointing direction and slewing maneuvers to rotate the satellite to alternate pointing directions. The requirements for each of these functions will vary depending on the mission. However, the range of the requirements can be ascertained, and such things as the velocity increments needed and the minimum thrust levels required for a particular mission and spacecraft size can be determined.

Stationkeeping for synchronous 24 hour equatorial satellite involves primarily north-south (cross-track), east-west (in-track), and radial perturbations. The perturbations are categorized as short-term and long-term. The short-term or orbital period oscillating forces are called diurnal, and those with periods greater than the orbital period are termed secular.

The repositioning maneuver is identical in function to the east-west stationkeeping maneuver, and is needed to obtain the desired satellite station location.

Orbit raising involves raising the satellite to synchronous orbit from some intermediate circular orbit reached by the launch vehicle. This is done in the low thrust mode which requires higher energy than the classical Hohmann transfer.

2. INITIAL POSITIONING

The initial positioning errors are primarily caused by the launch vehicle imparting errors to the spacecraft. Upon separating from the booster, the spacecraft will have a residual tumble rate in each axis which must be reduced to zero. The terminal velocity and position error must also be corrected. Eccentricity and inclination errors must be reduced to less than the allowable errors.

In general, the desired synchronous orbital plan velocity and altitude are not achieved exactly due to launch vehicle injection errors and dispersions in the apogee burn. The elimination of these residual errors is carried out by orbit trim maneuvers. The magnitude of the orbit trim maneuver is highly dependent upon the launch vehicle and the characteristics of the apogee kick motor, if used. Typical dispersions for the Thor Delta are on the order of 300 ft/sec; the Titan IIIC dispersions are between 80 and 125 ft/sec. When using low thrust for orbit raising, the errors are essentially within allowable limits at insertion.

The thrust levels needed to provide the above velocity increments are highly mission-dependent. If the initial positioning has to be performed rapidly, high thrust levels will be needed. Longer allowable times will permit lower thrust levels. The initial positioning maneuvers involve the

same functions as required in north-south, east-west, and radial corrections. These maneuvers are discussed in subsequent sections.

In addition to removal of injection errors needed to attain the desired circular equatorial synchronous orbit, it may still be necessary to move the satellite "in-track" to the desired initial station position and attain the desired spacecraft orientation. The allowable thrust levels and needed velocity increments to perform the initial station position maneuver are discussed in the section on repositioning as the two maneuvers are identical.

3. ATTITUDE CONTROL

Attitude control requires rotation of the satellite (slewing) to the desired pointing location and then stabilization at the desired position. Holding a desired pointing direction is accomplished by employing a stable limit cycle of operation over a desired deadband for three-axis stabilized spacecraft. Each time the satellite pointing direction exceeds the prescribed deadband, a set of thrusters is fired, driving it back into the deadband. If the perturbing force is so great that a minimum impulse firing does not change the direction of satellite rotation, the thrusters will continue to fire until the direction of rotation is reversed.

The perturbing torques are those caused by solar pressure and thrust misalignment of the stationkeeping system thrusters. If the center pressure (c.p.) is not coincidental with the spacecraft center of gravity (c.g.), solar pressure will have an effect on satellite attitude. The center of pressure will vary because of changes in reflectivity, distortion of the incident surfaces, and the changing areas presented to the sun as the spacecraft orbits the earth.

Figure 1 shows a typical stable limit cycle operation for satellite attitude control. In the figure, spacecraft angular velocity ω is plotted on the vertical scale and the spacecraft rotationl position Θ on the

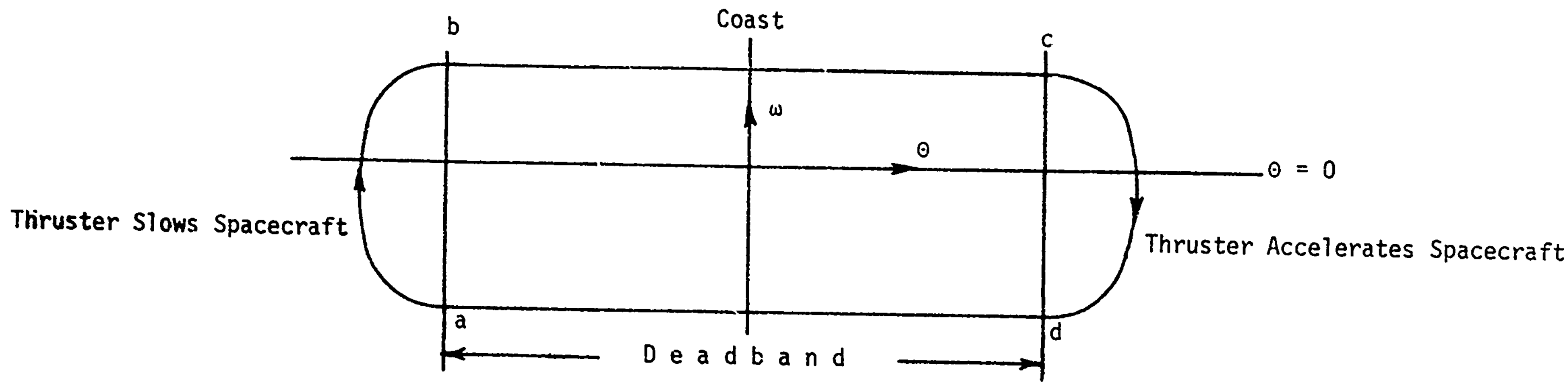

Fig. 1 Stable Limit Cycle Where Attitude Control System Torque is Much Greater Than Perturbing Torque

horizontal scale. The spacecraft coasts across the deadband from d to a and from b to c on its own momentum.

The thrusters operate from a to b and from c to d to change the direction of the spacecraft rotation. For specific thrust levels, the maximum propellant consumption occurs in a symmetric limit cycle operation and this assumption will be used in this analysis. In Ref. 2, it is shown that the total correction impulse which must be supplied to the spacecraft is

$$I_t = 1.5 \, [I_{ts} + I_{tlc}] \tag{2}$$

where I_{ts} is the total corrective impulse for solar pressure and I_{tlc} is the total limit cycle impulse delivered.

The factor, 1.5, results from a 50 percent contingency being applied for other disturbances such as torque caused by friction in moving parts, gravity gradient, earth magnetic field and coupling errors caused by thruster misalignment. It is shown in Ref. 3 that

$$I_{tlc} = \frac{I_{bit}^2 \, t_m}{\delta} \, \frac{r}{J} \tag{3}$$

and

$$I_{ts} = k \, t_m \, A \tag{4}$$

where I_{bit} = minimum impulse bit

t_m = time of mission in years

r = moment arm of thruster

J = moment of inertia

δ = deadband 1/2 angle

A = projected area of satellite in the direction of the sun

and k = a constant of proportionality.

This equation was assumed to be representative of the class of satellites under consideration and was used to calculate the total impulse from which the weight of propellant and required ΔV for attitude maintenance were also calculated. A minimum achievable angular rate of $2x10^{-4}$ deg/sec was assumed and the rate limit impulse was held to the minimum value when this rate was reached. A value of $\pm$ 0.125 degrees for deadband angle was used for coarse control and $\pm$ 0.100 for fine control.

For extremely fine pointing accuracies, say system pointing accuracies of 0.01° to 0.1°, a less sophisticated method was used to calculate total impulse. The required system pointing accuracy was used to enter Figure 2 (Ref. 3) for the configuration of the satellite and the required mission thruster on time. The impulse per pound of gross weight per day was read from the curves. For example. as shown by dashed lines on Figure 2, a required pointing accuracy of 0.1° for a cylindrical satellite and an on-time capability of 20 millisec results in an impulse per pound of gross weight per day of $8.5x10^{-4}$. Total impulse was then computed and the weight of propellant and ΔV increment was calculated from this value. Minimum thrust levels to achieve these pointing accuracies were investigated separately The final report presents results of only one value, $\pm$ 0.100°, as defined for fine control above.

4. STATIONKEEPING

The bulk of the geosynchronous satellites propulsion requirements for long mission duration satellites are for stationkeeping. A stationary geosynchronous satellite tends to drift from its initial position radially, longitudinally (in track), and latitudinally (cross-track). This drift is

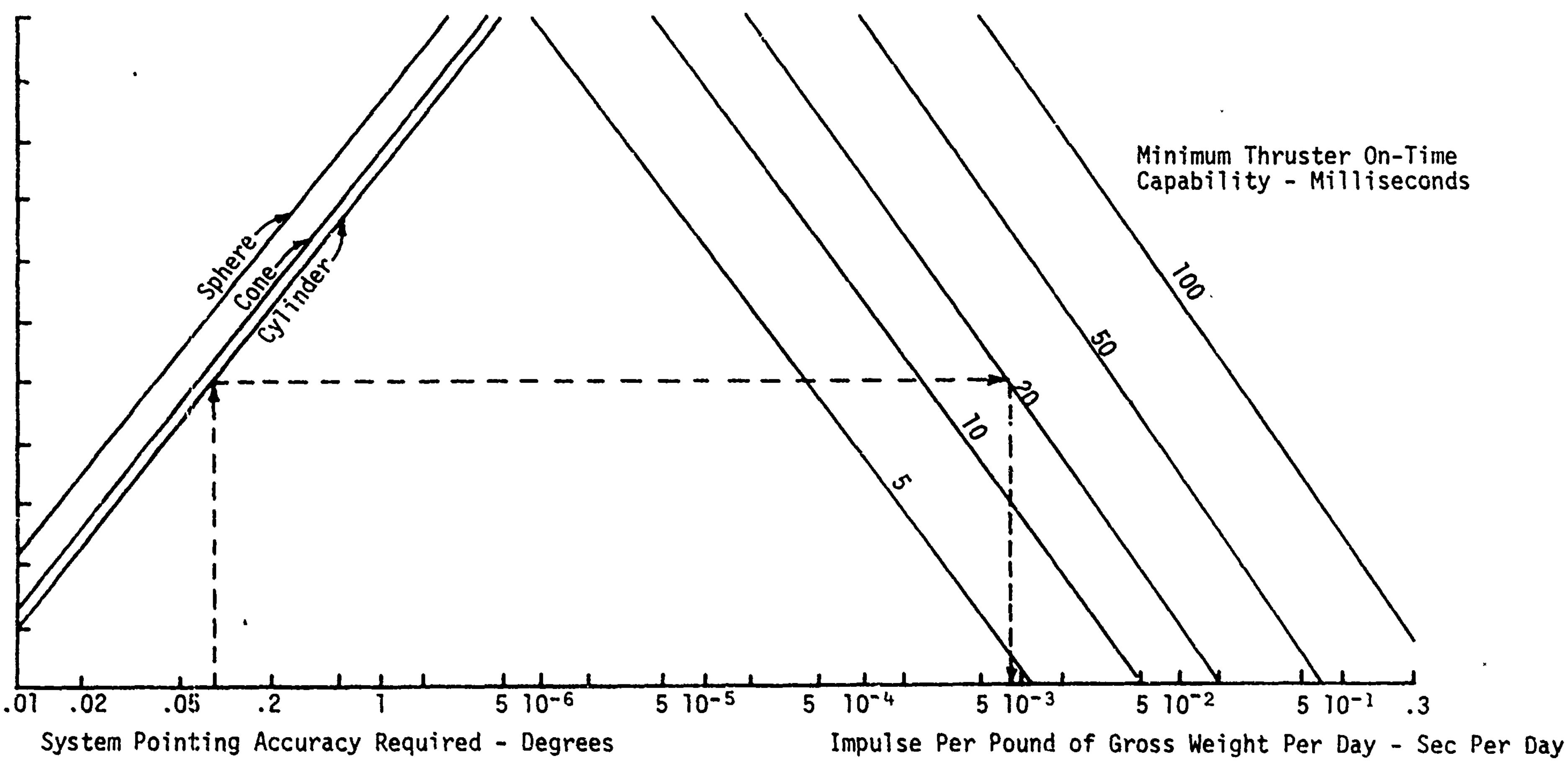

Fig. 2 Attitude Control Impulse Per Pound of Vehicle Weight for Vehicle Pointing (From Space Planners Guide)

caused by the asphericity of the earth and by the gravitational perturbations due to the sun and moon. These in-track and cross-track errors are called E-W and N-S stationkeeping errors and will continually increase unless cancelled.

This analysis considers two modes of stationkeeping. The fine mode will maintain the spacecraft in an orbit so closely that the periodic day by day displacements will have to be corrected. In this mode for instance, an annual ΔV increment of 635 ft/sec/yr will be required for stationkeeping (Ref. 4). In the course mode only those corrections related to the secular term will be corrected and here the control will only be to a degree that the periodic term will be negligible. This results in requiring a cross-track increment ΔV of about 150 ft/sec/yr and an in-track of about 7 ft/sec/yr for stationkeeping. To account for gimbaling or thrust vector control, 3% of the total ΔV increment was allotted for these functions except in the baseline case and the total impulse for stationkeeping was increased by this amount when applicable. No results were presented for the fine mode since no mission was identified when this mode was required.

5. NORTH-SOUTH STATIONKEEPING USING LOW THRUST

In the case of low-thrust propulsion, the required thrust for cross-track stationkeeping will have to be applied over an arc centered around the nodal crossings. The greater this arc, however, the less efficient the maneuver becomes. The efficiency of the maneuver varies with the angular distance from the nodal point. At 90 degrees from the nodal point, the application of thrust has no effect on plane change.

The maximum firing time then that can be employed to correct the cross-track perturbation is 1/2 the orbit time. Utilizing the maximum possible thruster firing time will result in a low thrust loss. The total impulse

determined utilizing the required velocity of increment for this maneuver will have to be increased. In Ref. 4, a factor of 1.57 was used and this factor is also used for this report. This is the penalty paid for using low-thrust, high-specific-impulse thrusters instead of the lower specific impulse, high-thrust devices.

The total system weight considerations indicate the desirability of using the lowest thrust possible. There is, however, a lower limit to the thrust that can be employed to impart the cross-track stationkeeping velocity increment requirement (needed for each half-orbital period) during the 12 hours available. Figure 3 illustrates this lower limit of thrust as a function of the required velocity increment and satellite weight for the mission analyzed and under the assumptions above. Any thrust level higher than these values would be suitable.

6. EAST-WEST STATIONKEEPING USING LOW THRUST

The direction of the low-thrust vector needed to remove the east-west perturbation is illustrated by Figure 4. The desired nominal synchronous orbit is shown by the dashed lines. The solid line indicates the perturbed orbit. This makes it necessary for the thruster to be gimballed or to have thrust vector control so the satellite can be maneuvered.

Earth-pointing spacecraft, with their spin axis in the orbital plane, have a similar problem in implementing this maneuver. This type of satellite usually incorporates a momentum wheel spin in a direction opposite to the spacecraft rotation, requiring larger velocity increments to accomplish east-west stationkeeping. This reduces the angular momentum to essentially zero and it can then be treated as a three-axis stabilized configuration with respect to energy expenditure for attitude control. The needed thrusting direction for this configuration is similar to the previous example.

7. REPOSITIONING WITH LOW THRUST

An aspect to be noted when selecting the thruster type to perform the maneuver is that using low-thrust devices requires a much larger velocity increment than is required for impulsive burning. This can readily be seen by referring to Figure 5, which shows the velocity time history in a qualitative sense. As shown, a situation can occur in which there is no coasting period when low-thrust devices are used. The engine fires for half the maneuver time and is constantly accelerating. The last half of the maneuver time is spent coasting at constant velocity. The area under each curve is the distance covered during the maneuver. For a specified relocation distance, the area of the triangle and rectangle must be equal. Therefore, the altitude of the minimum thrust time triangle is twice the altitude of the rectangle.

8. ORBIT RAISING AND LOWERING

In order to make a large change in orbit radius, the small acceleration of an electric propulsion thruster must be applied for a significant amount of time. In a high gravitational field, such as near the earth, this will require many orbital revolutions, resulting in the satellite travelling a spiral path. The most effective method of changing altitude with low thrust is to change orbit energy by applying the thrust perpendicular to the radius vector so that no energy is lost overcoming gravity. Applying thrust along this axis is almost the same as tangential thrusting (velocity vector thrusting) and for small accelerations they are essentially synonymous.

Acceleration applied in this manner to an initally circular orbit produces a spiral trajectory as shown in Figure 6. If the thrust is terminated, the satellite will be at one end of the latus rectum of the subsequent coast

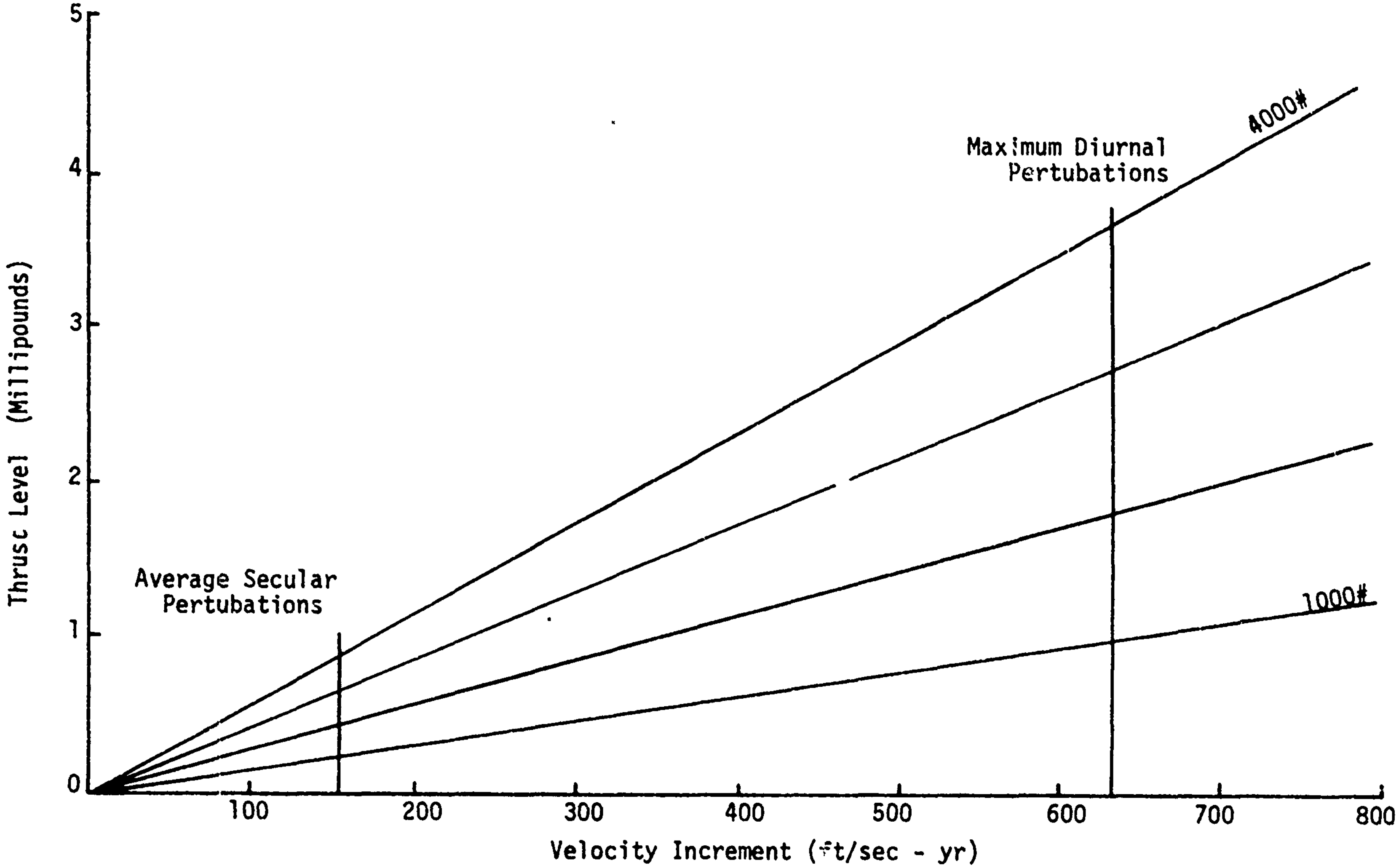

Fig. 3 Minimum Thrust Levels Required for North-South Stationkeeping vs Velocity Increment Required

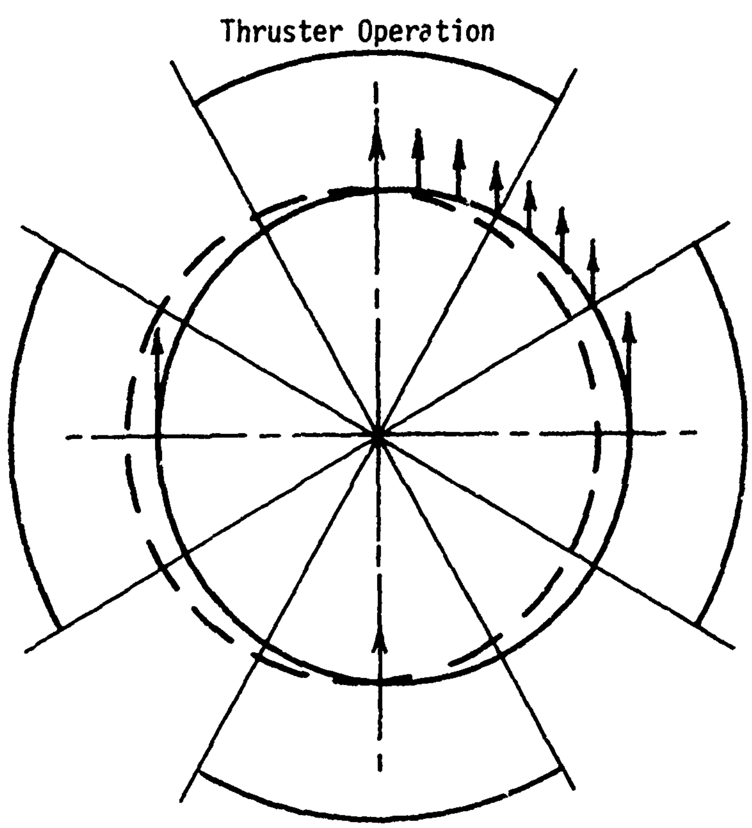

Fig. 4 Thrust Vector Direction to Remove East-West Drift
(Reference 3)

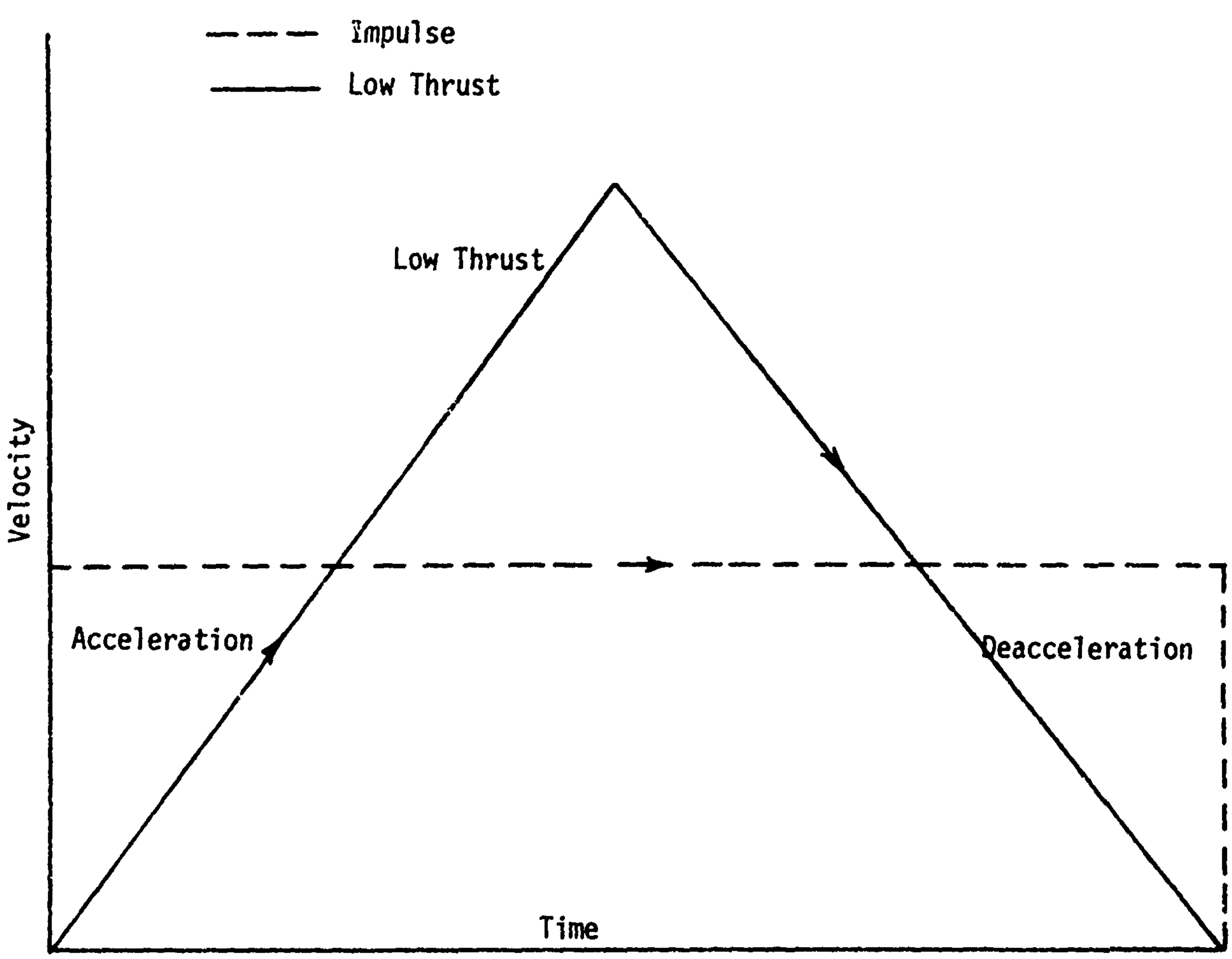

Fig. 5 Qualitative Comparison of Impulsive and Low Thrust Repositioning

ellipse. For small eccentricity, this is equivalent to being at one end of the major axis of the ellipse. It also results in a small thrust penalty because the thrust axis is misaligned from the velocity vector. Using the basic assumption of Ref. 5 (circular orbits), this results in the characteristic velocity being the negative of the change in orbital velocity or

$$\Delta V = V_1 - V_2 \tag{5}$$

where V_1 is the initial orbital velocity and V_2 is the final velocity.

$\frac{\Delta V}{V_1}$ is plotted in the upper curve of Figure 7. In transferring from a circular orbit radius r_1 to r_2 by the classical Hohmann transfer concept the velocity increment is that increment required to travel an ellipse with a semi-major axis given by

$$a = \frac{1}{2}(r_1 + r_2) \tag{6}$$

and a second increment required when reaching the opposite apsis of the ellipse. The total ΔV becomes (Ref. 5):

$$\Delta V = V_1 \left\{ \left(\frac{2R}{1+R}\right)^{\frac{1}{2}} \left(1 = \frac{1}{R}\right) - 1 + \left(\frac{1}{R}\right)^{\frac{1}{2}} \right\} \tag{7}$$

when $R = \frac{r_1}{r_2}$

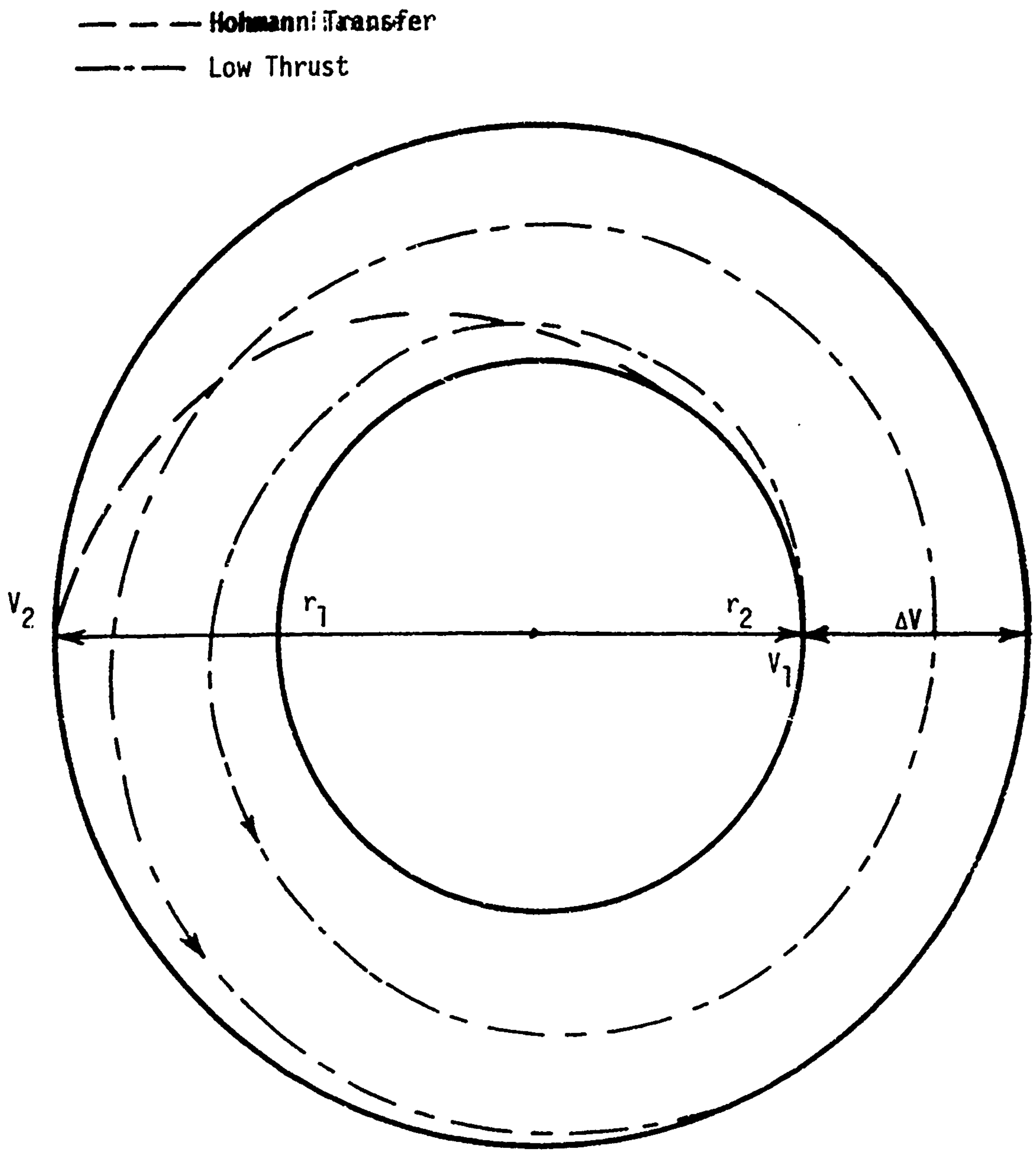

Fig. 6 Spiral Trajectory

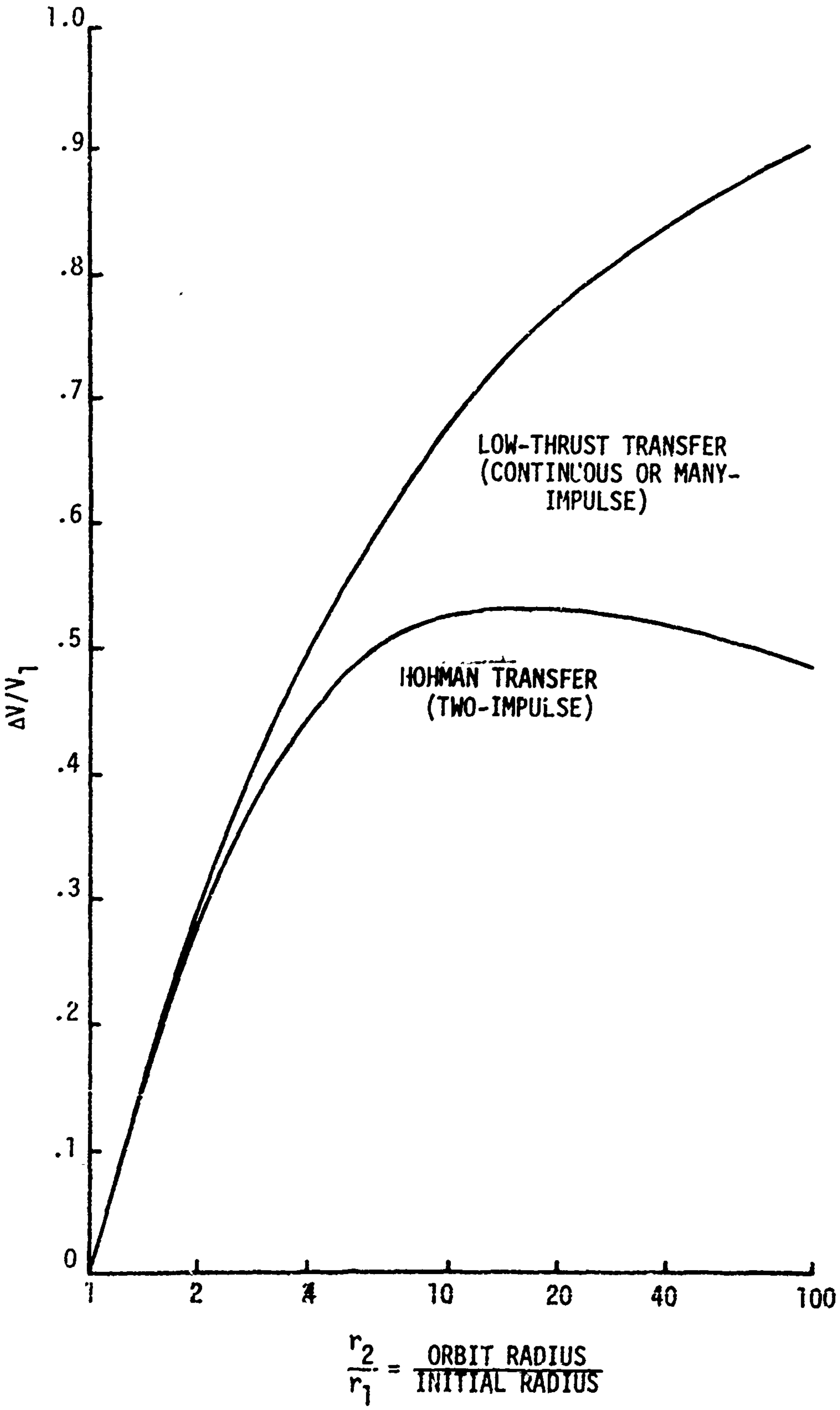

Fig. 7 Characteristic Velocity for Orbit Raising

The factor, $\frac{\Delta V}{V_1}$, from this formula is plotted as the lower curve in Figure 7. As can be seen, the penalty using the low thrust system is evident by comparing these curves. Also from this figure one can determine the approximate ΔV required to complete an optimal Hohmann transfer or low thrust maneuver given the appropriate initial conditions. The relationships above were used to correct the ΔV for the cases where orbit raising was considered. The time from intermediate orbit then was calculated from the formula $t = \frac{m \Delta V}{T}$, where m = mass, t = time, and T = thrust.

9. REPOSITIONING

A constellation of post-1975 satellites should be capable of covering any global region. This implies that the satellite has the capability to perform transfers of up to 180 degrees in longitude. For any given satellite thrust-to-weight ratio and change in satellite longitudinal position, a minimum time for repositioning can be determined. The velocity increment required is a function of the repositioning rate. The total ΔV required per reposition, using an impulsive maneuver, is given by the following equation (Ref. 2):

$$\Delta V_{rep} = \frac{2\, V_o}{3} \frac{\Delta \dot{P}}{P} \qquad (9)$$

where V_o = nominal orbit velocity (ft/sec)

P = orbital period (deg/day)

$\Delta \dot{P}$ = repositioning rate (deg/day)

For this analysis, a one-time satellite respositioning maneuver was assumed to be representative for a post-1975 synchronous satellite, and repositioning rate of 15 deg/day was used. The total ΔV_{rep} required for this

maneuver using Equation 9 is 280 ft/sec. It was shown in Fig. 4 that constant low thrust incurred a penalty for this maneuver. This penalty approximately doubles the required ΔV to reposition the satellite by low thrust devices.

The most efficient method for repositioning is to place the satellite into an orbit with a period slightly greater or less than 24 hours, causing a westward or eastward drift, respectively. Using this technique, repositioning requires from a few days to approximately 4 weeks.

SECTION V
PROPULSION SUBSYSTEMS

1. INTRODUCTION

The nine types of thrusters that form the basis of the propulsion subsystems considered are shown in Table 1. Two thrust levels were incorporated into each thruster system, the higher level being used for those propulsion functions where a high thrust was necessary to complete the task. The comparisons among types were made between propulsion subsystems performing the same task and designed to provide the same thrust levels except in the baseline system.

The baseline system was considered to have two thrust levels, not identical to the electric system, because the millipound monopropellant hydrazine thruster is not a practical subsystem. The baseline system accordingly has higher thrust levels than the other systems.

Fig. 8 gives a typical schematic diagram of the assumed configuration of the baseline system while Fig. 9 gives the corresponding diagram for the cesium (Cs) system. These are typical of the configuration for all the propulsion subsystems used in the study. A pressurization system similar to the schematic was necessary for all systems using liquid fuel.

For each electric propulsion technique a hybrid configuration was also postulated and analysis completed on these configurations. A typical schematic for these hybrid subsystems is shown in Fig. 10. The large monopropellant hydrazine thrusters were utilized to perform those functions where high thrust chemical propulsion devices were needed. The number of thrusters in the basic configuration for all propulsion subsystems utilized in this analysis are shown in Table 2, page 45. For the large thruster the number and placement of the thrusters were such that any maneuver could be performed by some

TABLE 1. THRUSTERS

Thruster Type	Nominal Thrust (lbf)
Chemical	
Monopropellant Hydrazine (N_2H_4)	Up to 5.0
Thermal Decomposition Resistojet	0.010
Electric	
Colloid	0.001 - 0.003
Magnetoplasmadynamic (MPD)	0.001 - 0.003
Pulsed Inductive Plasma	0.1 - 0.1
Ablative Teflon	0.001 - 0.003
Cesium Ion Bombardment (Cs)	0.001 - 0.003
Mercury Ion Bombardment (Hg)	0.001 - 0.003
Mercury Pulsed Plasma	0.001 - 0.003

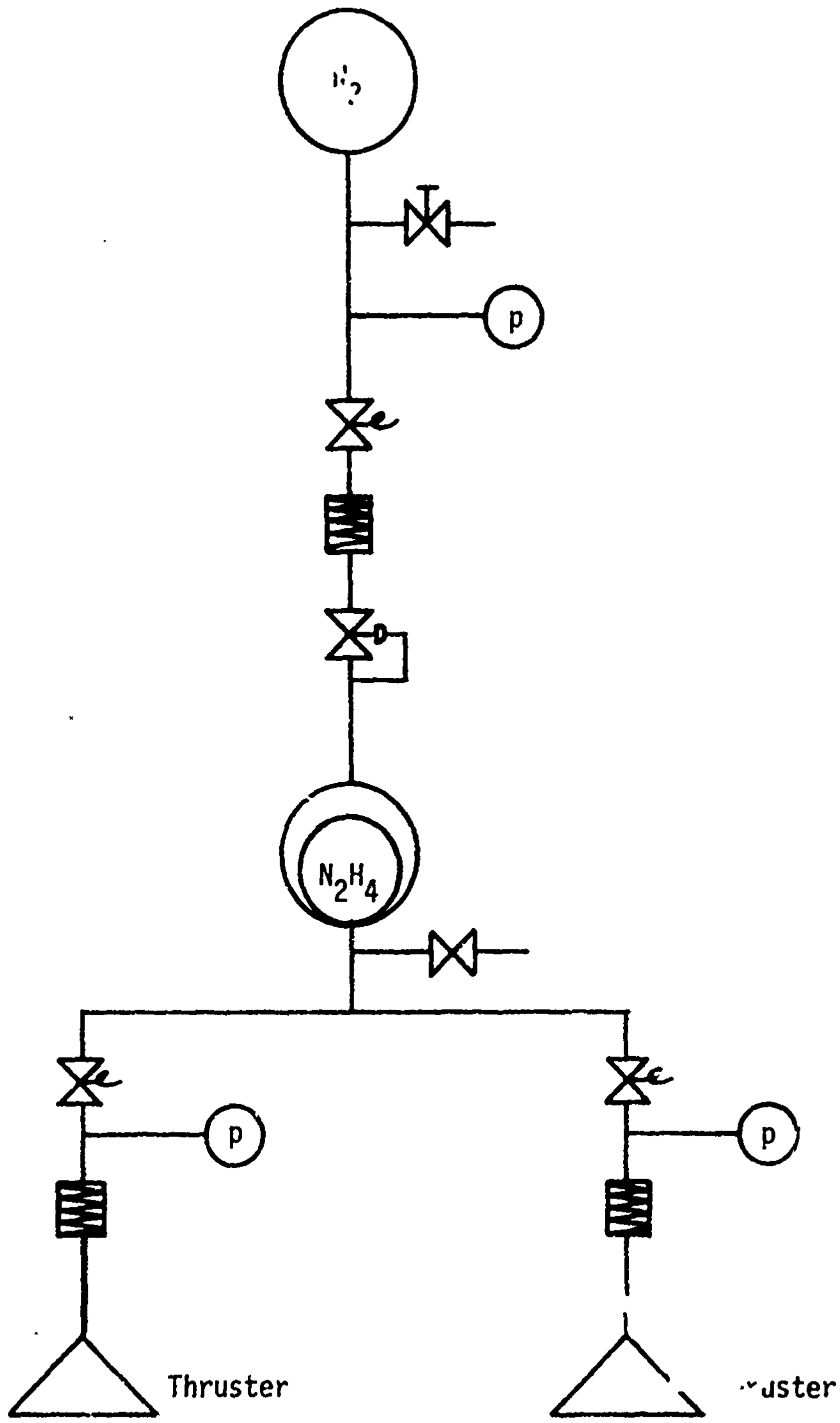

Fig. 8 Monopropellant Hydrazine Thrusters

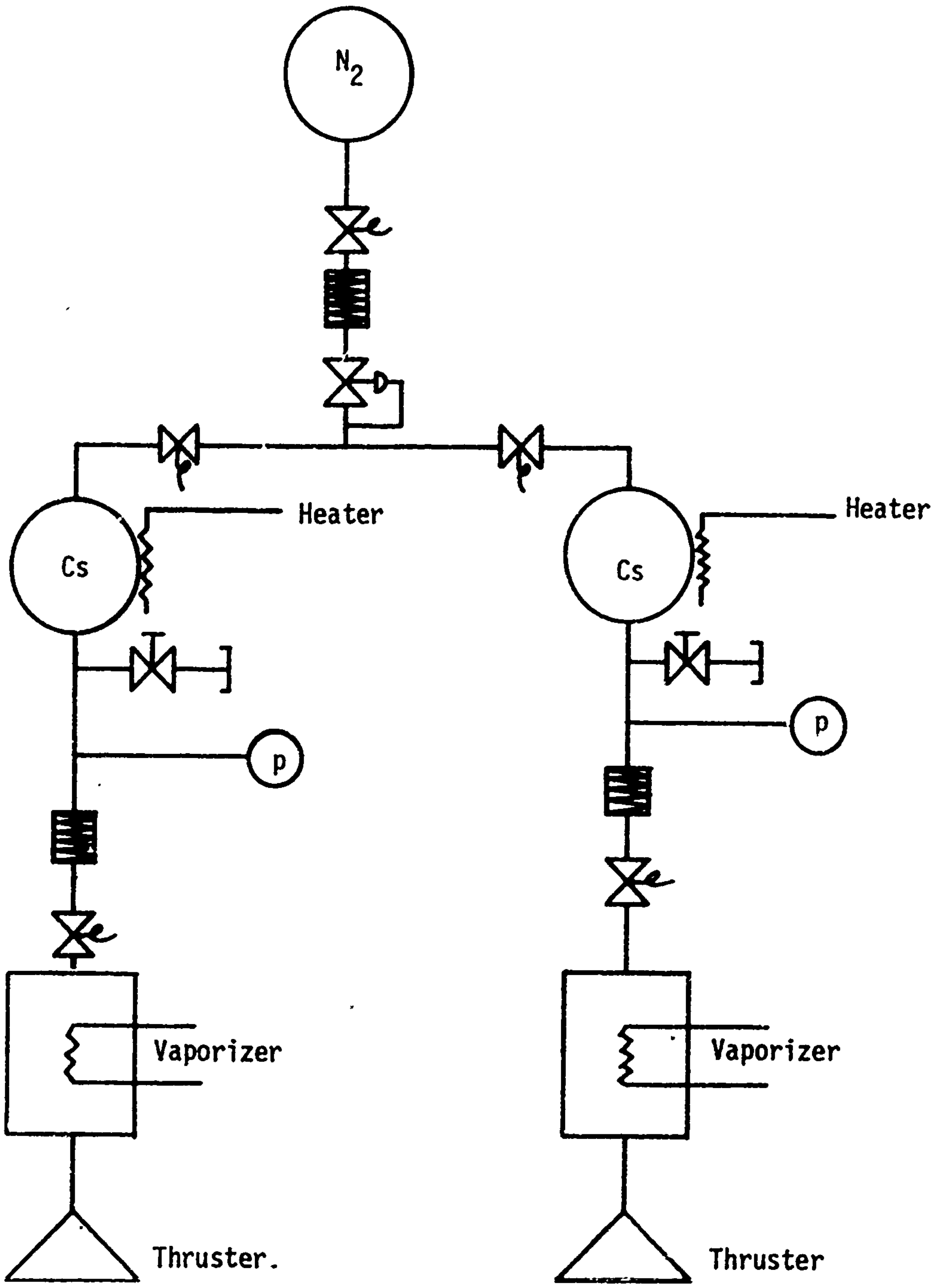

Fig. 9 Cesium Ion Thrusters

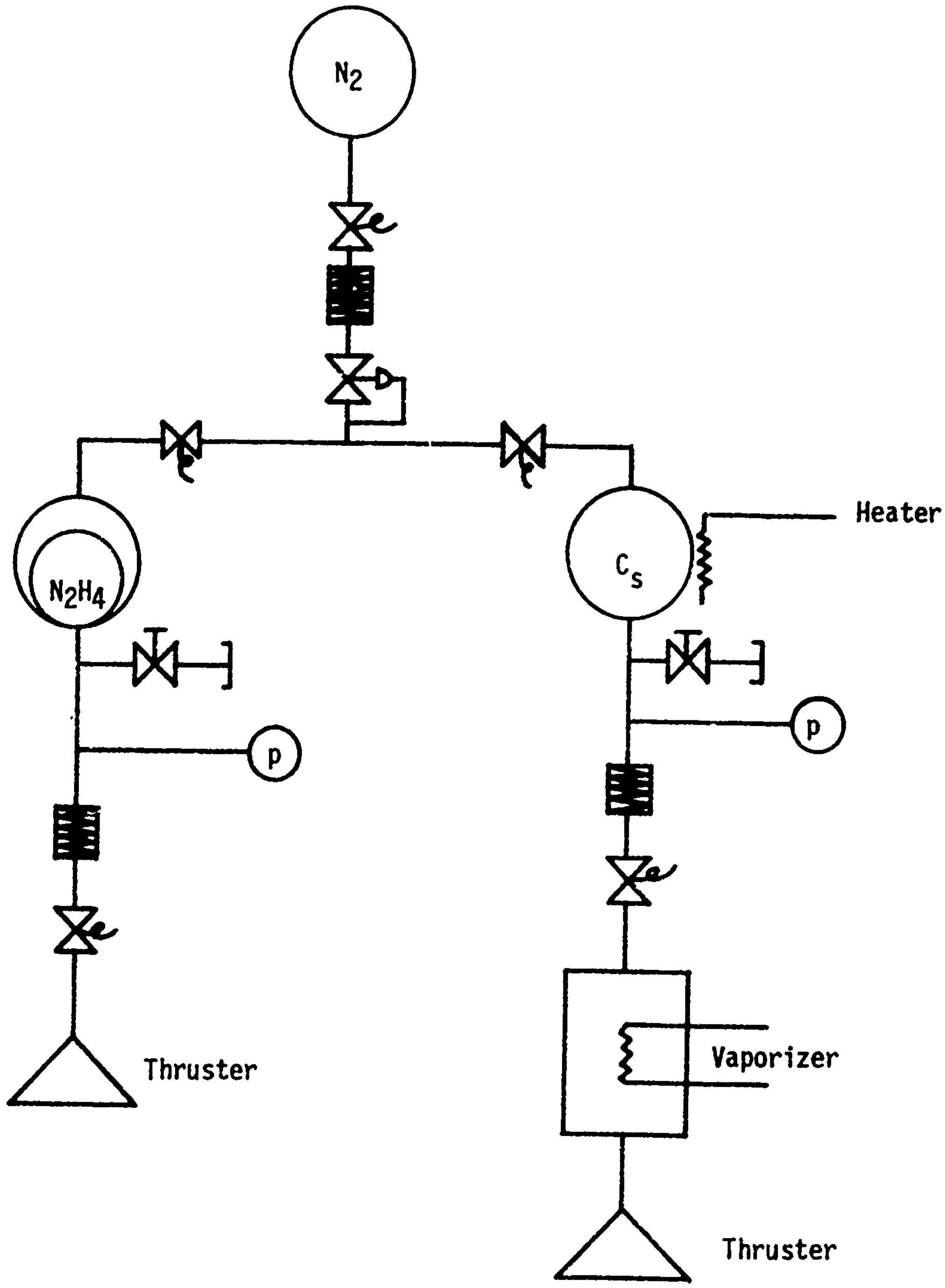

Fig. 10 Monopropellant Hydrazine/Cesium Hybrid Propulsion Subsystem

combinations of thrusters; however, for the smaller thrusters using electric propulsion devices it was necessary to postulate thrust vector control with its attendant degradation of thrust due to misallignment and the time required to rotate into position.

2. THRUSTER DESCRIPTIONS

a. N_2H_4 Catalytic Hydrazine Thrusters. The monopropellant hydrazine thruster is the "standard" spacecraft propulsion system for missions that do not have stringent orientation requirements and are not marginal on weight. Hydrazine has excellent storability, good compatibility with most engineering materials, and is capable of repeated pulsed operations.

Large thrusters up to 5 pounds of thrust are readily available. The only power necessary is for approximately 3 watt heaters for each thruster and a small amount of power for the solenoids. In the ideal configuration assumed, there were 8 large thrusters and 12 small thrusters resulting in a power requirement of 80 watts. The weight of the thrusters and associated equipment is 14.8 pounds. The capabilities assigned to the thrusters are 0.1 pounds of thrust for the smaller thrusters and 5 pounds of thrust for the large thrusters. Selection of smaller thrust capabilities would reduce the weight by only a small amount. A minimum impulse bit of 4×10^{-3} pound-sec was used resulting in a specific impulse of 200 seconds. The large thrusters were given a specific impulse of 230 seconds which represents the maximum achievable with hydrazine. Figure 8 gives a schematic diagram of the system used as the reference.

b. Electric Bombardment Engines. The electric bombardment engines use an annode-cathode arrangment to ionize a propellant such as mercury or cesium.

The ions are accelerated in an electro-static field and neutralized as they are emitted to avoid a space charge flow. The ionization potential of cesium is less than that of mercury; however, the electron interaction for mercury is greater than that of cesium resulting in both propellants being equally easy to ionize. Cesium is easily handled by passive zero-g feed systems and has a high mass utilization efficiency as long as it is kept above its freezing point. High frequency pulsing is not considered in this analysis. The power requirements are sensitive to the thrust required. The configuration used in this analysis is shown schematically in Fig. 9.

c. Colloid. The basis for the colloid engine is an electrically conducting propellant subjected to a high electric field established between the propellant and an extractor electrode. This engine, like an ion thruster, produces thrust by accelerating charged particles through an electric field. The extractor electrode has historically been mall-diameter (4-mil bore) capillary needle, but recent development effort has been expended on a linear slit geometry electrode version. Once the electrode field is established, field emission ionization of small-diameter droplets occurs at the needle tip or linear slit. The same field which produces ionization also accelerates the charged droplets to produce thrust. Since the charged droplets may be positive or negative depending on the polarity of the potential applied to the needles, a neutralizer is necessary to neutralize the beam. The masses of the charged droplets are generally greater than the masses of ions produced in ion engines.

A liquid propellant, normally glycerol with 19.3 percent by weight sodium iodide, is fed into the needle. The emitting rim of the needle is centered within the circular aperture of the extractor electrode. The miniscus at the

end of the needle forms microscopic jets which accentuate the electric field (10^7v/cm) causing a continuing emission and acceleration of invisible, charged colloid droplets (approximately 100Å in diameter). The needles are generally held at a positive potential of 5 to 10 kv. The extractor electrode (aperture) is maintained at a negative potential of approximately -500 to -1000 volts.

A thrust of 5 μlb_f per needle can be obtained, which may be throttled doen to 1 μlb_f by decreasing the propellant flow rate or reducing the capillary potential. Similarly, the specific impulse may be varied between 600 and 1500 lb_f.s/lb_m. Higher thrusts are achieved by grouping many needles.

d. MPD. The MPD thruster is constructed in an annode-cathode arrangement with propellant injected in between. Magnetic coils surround the structure. As a result of the potential difference between annode and cathode, an arc is produced which heats the propellant. The magnetic field keeps the arc moving over the cathode surface. By reduction of pressure in the chamber between annode and cathode, high ratios of power to mass flow are obtainable with relative high specific impulses.

e. Ablative Teflon. This thruster uses sticks of teflon as a propellant; otherwise, the operation is similar to the other types of thruster. The required power to thrust ratios were obtained through verbal communication with Mr. Edward Barth of the Rocket Propulsion Laboratory. The poor performance of this engine depicted in this analysis is a result of the basic characteristic used. Improvement in performance could be obtained by reducing the power to thrust ratio, reducing the weight, and changing the Isp to an optimum value; however, for the missions considered in this analysis. performance would still be lower than that of the mercury hybrid subsystem.

3. DISCUSSION

The number of thrusters required for each propulsion subsystem, shown in Table 2, was determined from the weight of the satellite, the minimum thrust required, and the thrust available per thruster. The subsystem was sized to allow the thrusters to provide north-south stationkeeping when operating from 40 - 50 percent of the time since this was the most demanding task to be performed by the subsystem.

The corresponding weights of the thrusters are shown in Table 3. The weight listed under the heading "Other" in the table are weights that are common to both small and larger thrusters and consist of the weight of added structure and components not part of the thrusters. Table 4 shows the electrical power requirements for each type of subsystem. The values were obtained from many sources and represent reasonable, achievable thrust power ratios. The weight of the power conditioning (PC) unit required for each type of electrical propulsion is also shown in the table.

Table 5 presents the weight of the total attitude control subsystem utilizing each type of propulsion subsystem. The total weight consists of the weight of the propulsion subsystem and that of the guidance and control subsystem. The aggregate weight is broken down into propellant weight and dry weight and these weights are shown as a function of the mean mission duration and weight category of the satellite. It will be observed that employment of electrical propulsion results in substantial savings in the weight of propellants. The cesium in an all cesium propulsion subsystem in a 3-year small category satellite would weigh only 12.2 pounds compared with 135.9 pounds of hydrazine required for a comparable satellite using a monopropellant hydrazine subsystem. This saving in weight is offset in

part by the relatively heavier thrusters (Table 3) and power conditioning (Table 4) required for the cesium ion propulsion subsystem. The net reduction in the weight of the attitude control subsystem is 101.3 pounds (Table 5). A similar analysis of the saving in attitude control subsystem weight that would result from use of any of the propulsion subsystems under consideration can be made from the data in the above cited tables. For example, if interest centers upon the hybrid mercury propulsion subsystem, it will be found that employment of the hybrid mercury subsystem would result in net saving of 114.6 pounds in the weight of the attitude control subsystem of a 3-year satellite.

Conclusions as to the desirability of employing a particular type of propulsion subsystem cannot be based exclusively on the potential reduction in the weight of the attitude control subsystems because of the interaction between this subsystem weight and the weights of other major subsystems. For instance, use of electric propulsion increases the weight of the electric power supply subsystem and reduces the structural weight of the satellite. Consideration of the interaction of the subsystem weights and the reduction in the total weight of the satellite is deferred to Section VII, Satellite Weight Analysis.

TABLE 2

NUMBER OF THRUSTERS ASSUMED IN THE PROPULSION SUBSYSTEMS

Type of Propulsion Subsystem	Small Category Satellites		Medium Category Satellites		Large Category Satellites	
	Small Thrusters	Large Thrusters	Small Thrusters	Large Thrusters	Small Thrusters	Large Thrusters
Mono. Hydrazine	8	12	8	12	8	12
N_2H_4/Resistojet	8	12	8	12	8	12
Cesium	0	2	0	3	0	4
N_2H_4/Cesium	8	1	8	2	8	3
Colloid	0	2	0	3	0	4
N_2H_4/Colloid	8	1	8	2	8	3
Mercury	0	2	0	3	0	4
N_2H_4/Mercury	8	1	8	2	8	3
Ablative Teflon	0	2	0	3	0	4
N_2H_4/Teflon	8	1	8	2	8	3
MPD	0	2	0	3	0	4
N_2H_4/MPD	8	1	8	2	8	3

TABLE 3

THRUSTER WEIGHTS FOR ALL PROPULSION SUBSYSTEMS USED IN STUDY

(In pounds)

Type of Propulsion Subsystem	Small Category Satellites				Medium Category Satellites				Large Category Satellites			
	Large	Small	Other	Total	Large	Small	Other	Total	Large	Small	Other	Total
Mono. Hydrazine	6.4	4.8	9.6	20.8	6.4	4.8	9.6	20.8	6.4	4.8	9.6	20.8
N_2H_4/Resistojet	6.4	2.7	8.9	18.0	6.4	5.4	11.6	22.4	6.4	8.1	12.3	26.8
Cesium	0.0	44.0	7.0	51.0	0.0	66.0	11.0	77.0	0.0	88.0	14.0	102.0
N_2H_4/Cesium	6.4	22.0	10.0	38.4	6.4	44.0	15.3	65.7	6.4	66.0	17.5	91.9
Colloid	0.0	30.0	4.0	34.0	0.0	36.0	11.0	52.0	0.0	60.0	9.0	69.0
N_2H_4/Colloid	6.4	15.0	8.5	29.9	6.4	30.0	13.0	49.4	6.4	45.0	16.5	67.9
Mercury	0.0	24.0	5.0	29.0	0.0	36.0	7.0	43.0	0.0	48.0	8.0	56.0
N_2H_4/Mercury	6.4	12.0	7.5	25.9	6.4	24.0	11.3	41.7	6.4	36.0	14.0	56.4
Ablative Teflon	0.0	50.0	7.0	57.0	0.0	75.0	10.0	85.0	0.0	100.0	13.0	113.0
N_2H_4/Teflon	6.4	25.0	8.0	39.4	6.4	50.0	14.0	68.4	6.4	75.0	15.0	96.4
MPD	0.0	80.0	11.0	91.0	0.0	120.0	14.0	134.0	0.0	160.0	16.0	176.0
N_2H_4/MPD	6.4	40.0	11.0	57.4	6.4	80.0	14.0	100.4	6.4	120.0	15.6	142.0

TABLE 4

THRUSTER END OF LIFE POWER AND POWER CONDITIONING (PC) WEIGHTS FOR ALL PROPULSION SUBSYSTEMS USED IN STUDY

(3 yr MMD)

Type of Propulsion Subsystem	Small Category Satellites				Medium Category Satellites				Large Category Satellites			
	Thruster Power		Total Power (Watts)	PC Wt. (lbs)	Thruster Power		Total Power (Watts)	PC Wt. (lbs)	Thruster Power		Total Power (Watts)	PC Wt. (lbs)
	Large (Watts)	Small (Watts)			Large (Watts)	Small (Watts)			Large (Watts)	Small (Watts)		
Mono. Hydrazine	32	48	600	0.0	32	48	1,080	0.0	32	48	1,520	0.0
N_2H_4/Resistojet	32	31	583	1.0	32	64	1,096	1.5	32	96	1,568	2.0
Cesium	---	260	260	10.0	---	390	1,390	13.0	---	520	1,960	16.0
N_2H_4/Cesium	32	130	692	10.0	32	260	1,292	13.0	32	390	1,862	13.0
Colloid	---	98	618	7.0	---	147	1,147	10.0	---	196	1,636	13.0
N_2H_4/Colloid	32	49	601	7.0	32	98	1,130	10.0	32	147	1,619	10.0
Mercury	---	130	700	5.0	---	270	1,270	7.0	---	360	1,800	9.0
N_2H_4/Mercury	32	90	642	5.0	32	180	1,212	7.0	32	270	1,742	7.0
Ablative Teflon	---	350	870	10.0	---	525	1,525	14.0	---	525	1,997	18.0
N_2H_4/Teflon	32	175	727	10.0	32	350	1,382	14.0	32	700	2,140	14.0
MPD	---	240	760	6.0	---	360	1,360	8.0	---	480	1,920	10.0
N_2H_4/MPD	32	120	672	6.0	32	240	1,272	8.0	32	360	1,832	8.0

TABLE 5

ATTITUDE CONTROL SUBSYSTEM WEIGHTS - SMALL CATEGORY SATELLITES
(In pounds)

Type of Propulsion Subsystem	3 Year			4 Year			5 Year			7 Year		
	Propel-lant	Dry	Total	Propel-lant	Dry	Total	Propel-lant	Dry	Total	Propel-lant	Dry	Total
Mono. Hydrazine	135.9	132.5	268.4	180.6	149.9	330.5	227.3	173.7	401.0	345.9	207.9	553.8
N_2H_4/Resistojet	123.3	126.2	249.5	166.0	143.1	309.1	213.7	164.9	378.6	323.5	198.4	521.9
Cesium	12.2	154.9	167.1	16.1	168.4	184.5	20.5	194.2	214.7	30.3	229.1	259.4
N_2H_4/Cesium	31.5	140.5	172.0	38.8	153.9	192.7	46.3	177.0	223.3	61.8	208.2	270.0
Colloid	29.5	127.7	157.2	39.1	141.5	180.6	49.8	161.7	211.5	73.9	192.4	266.3
N_2H_4/Colloid	43.3	126.3	169.6	55.3	139.3	194.6	68.1	160.5	228.6	95.8	188.8	284.6
Mercury	16.8	119.2	136.0	22.2	131.6	153.8	28.2	151.7	179.9	41.7	178.4	220.1
N_2H_4/Mercury	35.5	118.3	153.8	44.4	131.0	175.4	53.5	150.9	204.4	72.5	177.1	249.6
Ablative Teflon	25.0	161.2	186.2	32.7	174.9	207.6	59.7	201.5	243.2	62.2	237.8	300.0
N_2H_4/Teflon	42.8	142.1	184.9	54.1	155.5	209.6	66.0	178.6	244.6	91.7	210.0	301.7
MPD	15.9	195.4	211.3	20.9	251.5	230.6	26.7	243.1	269.8	39.7	288.4	328.1
N_2H_4/MPD	34.3	158.2	192.5	42.5	171.9	214.4	51.1	198.5	249.6	70.1	233.6	303.7

TABLE 5 (continued)

ATTITUDE CONTROL SUBSYSTEM WEIGHTS - MEDIUM CATEGORY SATELLITES

(In pounds)

Type of Propulsion Subsystem	3 Year			4 Year			5 Year			7 Year		
	Propel-lant	Dry	Total	Propel-lant	Dry	Total	Propel-lant	Dry	Total	Propel-lant	Dry	Total
Mono. Hydrazine	252.3	196.9	459.2	355.6	225.2	580.8	458.8	261.4	720.4	696.5	313.9	1010.4
N_2H_4/Resistojet	242.4	197.1	439.5	332.7	225.0	557.7	434.1	261.5	695.6	667.5	313.8	981.3
Cesium	23.5	235.6	259.1	31.4	256.9	288.3	40.3	296.3	336.6	60.0	349.7	409.7
N_2H_4/Cesium	53.5	226.2	279.7	67.9	247.9	315.8	83.4	285.4	368.8	117.8	336.6	454.4
Colloid	57.6	201.3	258.9	77.8	222.1	299.9	99.8	256.2	356.0	148.0	302.4	450.4
N_2H_4/Colloid	79.1	203.0	282.1	104.0	224.5	328.5	135.3	258.9	394.2	195.3	305.7	501.0
Mercury	31.7	182.4	214.1	43.0	201.7	244.7	55.0	232.6	287.6	82.1	273.5	355.6
N_2H_4/Mercury	60.4	188.9	249.3	77.6	209.3	286.9	96.4	241.2	337.6	137.6	283.9	421.7
Ablative Teflon	49.7	251.5	301.2	66.5	273.6	340.1	85.7	315.5	401.2	132.7	371.9	504.6
N_2H_4/Teflon	77.2	234.9	312.1	99.7	256.9	356.6	124.7	295.8	420.5	180.5	348.5	529.0
MPD	30.3	292.9	323.2	40.4	314.9	355.3	52.0	364.3	416.3	77.8	433.2	511.0
N_2H_4/MPD	59.6	259.5	319.1	75.9	281.6	357.5	94.0	326.0	420.0	133.8	386.2	520.0

TABLE 5 (continued)

ATTITUDE CONTROL SUBSYSTEM WEIGHTS - LARGE CATEGORY SATELLITES

(In pounds)

Type of Propulsion Subsystem	3 Year			4 Year			5 Year			7 Year		
	Propel-lant	Dry	Total	Propel-lant	Dry	Total	Propel-lant	Dry	Total	Propel-lant	Dry	Total
Mono. Hydrazine	394.2	260.0	654.2	538.6	298.5	837.1	697.1	347.1	1044.2	1062.9	416.9	1479.8
N_2H_4/Resistojet	366.0	265.2	631.2	506.7	303.6	810.3	661.9	353.1	1015.0	1022.0	424.3	1446.3
Cesium	34.9	314.2	249.1	47.1	342.9	390.0	60.1	395.8	455.9	90.2	461.1	551.3
N_2H_4/Cesium	80.9	309.9	390.8	104.3	339.1	443.4	128.5	390.7	519.2	181.9	461.1	643.0
Colloid	86.9	272.2	359.1	110.0	308.7	418.7	152.2	346.5	498.7	228.4	409.3	637.7
N_2H_4/Colloid	120.4	274.1	394.5	158.6	303.2	461.8	199.8	350.1	549.9	291.3	411.2	702.5
Mercury	49.1	249.3	298.4	66.5	276.3	342.8	85.3	318.5	403.8	127.4	374.3	501.7
N_2H_4/Mercury	91.8	255.2	347.0	119.2	283.0	402.2	148.3	326.6	474.9	162.6	434.2	596.8
Ablative Teflon	73.7	335.7	409.4	99.3	365.4	464.7	127.3	421.4	548.7	190.7	496.8	687.5
N_2H_4/Teflon	117.1	318.1	435.2	152.8	348.3	501.1	191.2	401.8	593.0	277.3	473.9	751.2
MPD	44.9	388.4	433.3	60.5	418.0	478.5	77.8	484.6	562.4	116.5	574.9	691.4
N_2H_4/MPD	90.5	356.2	446.7	116.4	386.5	502.9	144.6	448.0	592.6	205.8	531.2	737.0

SECTION VI

COMPUTER PROGRAM

1. INTRODUCTION

The computer program functional diagram is shown in Fig. 11. The basic program is taken from an RPL Report (Ref. 2), and the reader is referred to that report for specific details concerning the basic program. The Centerbody Weight, moment of inertia, maximum projected area, propellant tank size and weight and pressurization systems are identical to the RPL program; however, the calculations for impulse, ΔV, and propellant for the mission functions and the solar panel size and weight subprograms were modified. The discussion that follows will address only those changes which were introduced in these parts.

2. CALCULATION OF SOLAR PANEL WEIGHT

The total on board power was determined by adding the mission power to the power required for the propulsion system. The mission power was determined from typical mission requirements and was held constant for each class of satellite. The electrical propulsion power requirements were determined for the particular type of thruster and the thrust requirements under consideration. This power was calculated from appropriate electrical power to thrust ratios as determined from technical reports and personal interviews. When the total power was known the panels were then sized and weighed using the ideal specific weight, percent life degradation as a function of MMD, specific surface area and height-to-length ratio. The value of the above parameters utilized in the mission study were from a Lockheed NASA study (Ref. 6) and represent a medium hardened array utilizing solar cells available in the 1974 time period and represent a realistic achievable power system.

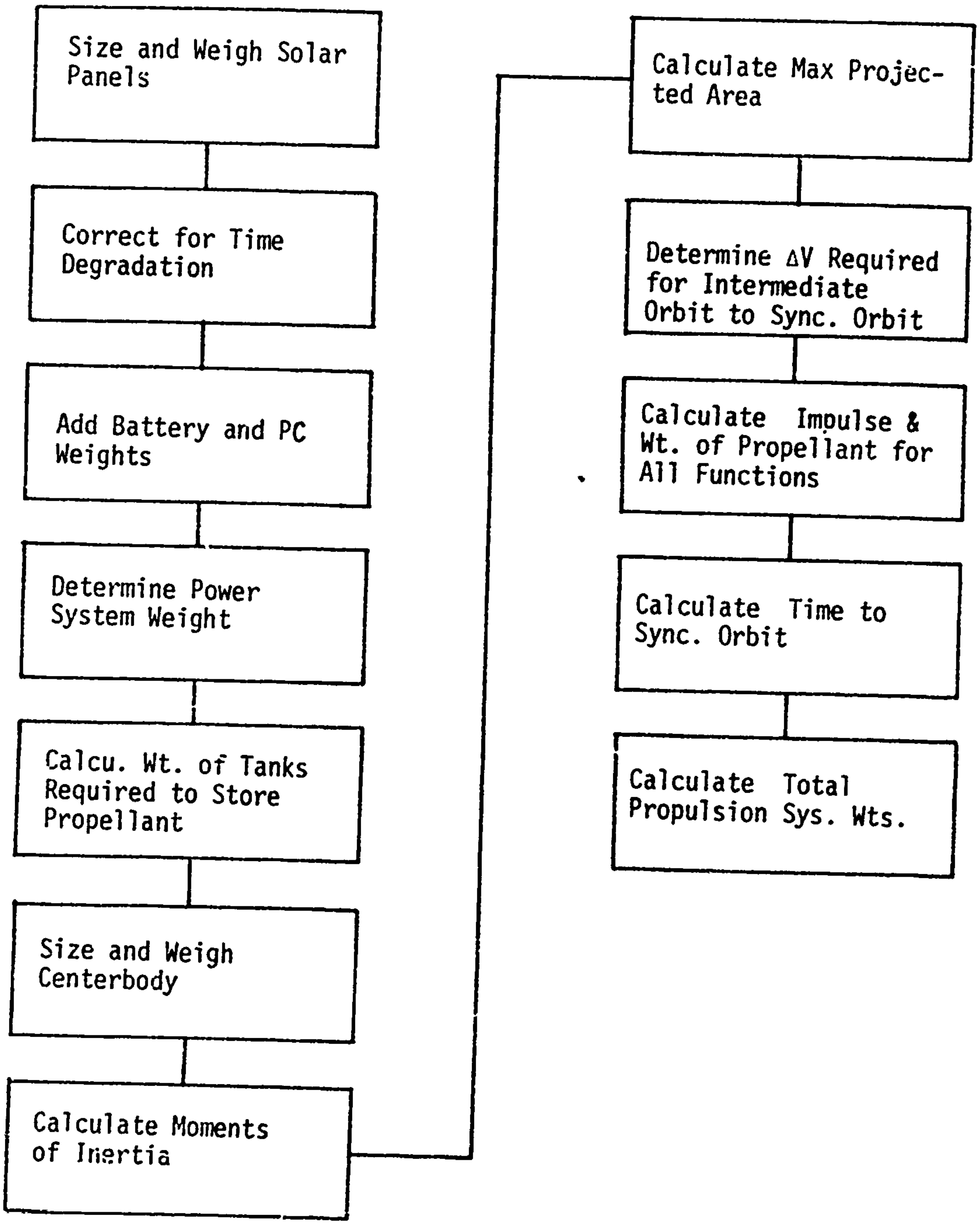

Fig. 11 Computer Program

The mission functions are calculated in the order shown in Table 6. It has been assumed that the satellite was placed into the proper position for minimizing the ΔV changes required for repositioning and stationkeeping. The satellite repositioning maneuver was required half way through the mission. Any mission function can be assigned a ΔV of zero with the required propellant weighing 0.0 pounds.

A spiraling mode is included in the program. The ΔV is read in as input data. The value was obtained from Table 14, page 100. Spiraling times were then calculated for each launch vehicle used in the analysis.

TABLE 6

MISSION FUNCTIONS

1. Spiraling to orbit
2. Despin
3. Tipoff
4. Injection
5. One-half of the total E-W stationkeeping
6. One-half of the total N-S stationkeeping
7. One-half of the total attitude maintenance, i.e., solar pressure, limit cycle and contingency.
8. Repositioning
9. One-half of the total E-W stationkeeping
10. One-half of the total N-S stationkeeping
11. One-half of the total attitude maintenance
12. Stationkeeping contingency
13. Apsidal control
14. Nodal regression
15. Spiraling from orbit

SECTION VII

SATELLITE WEIGHT ANALYSIS

1. INTRODUCTION

To appraise the effectiveness of potential application of electric propulsion in the operation of satellites, it was necessary to estimate the weight and other characteristics of the five major subsystems of each type of satellite under study. The major subsystems are (a) structure, including thermal control and interstage, (b) telemetry, tracking and command (TT & C), (c) communications, which is the mission package, (d) electric power supply, and (e) attitude control. Weights of the solar panels, propellant tanks and propellants were generated by the computer program. The weights assigned to other elements of the electric power supply subsystem and the attitude control subsystem were based upon studies of electric propulsion systems and information obtained from contractors. Weights of the other three major subsystems, namely, structure, TT & C and communications were estimated from weight data available from twelve satellite programs. The procedure followed in determining the subsystem weights is explained in Appendix A.

2. WEIGHT AS A FUNCTION OF SATELLITE LIFE

Enhancement of the mean mission duration (MMD) of a satellite results in increased weight required to provide adequate redundance, propellants, electric power and structure. The procedure followed in estimating the increased weight of the satellites is illustrated in Table 7. The weight growth factors were computed from data in an Aerospace Corporation report (Ref. 7). The resultant estimates of the subsystem weights of a small category satellite with a monopropellant hydrazine propulsion subsystem are shown in the table. Comparable subsystem weights and the total weight of each of the other eleven

TABLE 7

INCREASE IN SATELLITE WEIGHT ASSOCIATED WITH ENHANCEMENT OF MEAN MISSION DURATION (MMD)

Satellite Subsystem	Weight Growth Factors Associated with Increase in MMD			Weight of Satellite with Monopropellant Hydrazine (N_2H_4) Propulsion Subsystem (lbs)			
	3 to 4 Yrs.	3 to 5 Yrs.	4 to 7 Yrs.	3 Years	4 Years	5 Years	7 Years
Structure	1.067	1.115	1.096	211.5	225.7	235.8	247.4
TT and C	1.004	1.085	1.198	70.0	70.3	76.0	84.2
Communications	1.197	1.333	1.280	219.0	262.1	291.9	335.5
Electric Power:							
Elec. Distribution	1.011	1.025	1.102	69.0	69.8	70.7	76.9
Power Control	1.000	1.025	1.159	31.0	31.0	31.8	35.9
Batteries	1.000	1.025	1.334	88.5	88.5	90.7	118.1
Solar Panels	(a)	(a)	(a)	42.6	42.9	43.1	43.9
Attitude Control:							
Controls	1.145	1.319	1.343	96.3	110.3	127.0	148.1
Power Conditioning	1.000	1.025	1.159	--	--	--	--
Thrusters	1.000	1.176	1.426	20.8	20.8	24.5	29.7
Tanks: N_2H_4	(a)	(a)	(a)	12.3	14.7	17.0	22.2
Propellant: N_2H_4	(a)	(a)	(a)	135.9	180.6	227.3	345.9
Nitrogen System	(a)	(a)	(a)	3.1	4.1	5.2	7.9
Total Satellite Weight				1000.0	1120.8	1241.0	1495.7

(a) Increase in weight was determined by the computer program.

types of small category satellites are given in Appendix B, Table B1. Corresponding weight data for medium category satellites are shown in Table B2 of the same appendix. The estimates for large category satellites are in Table B3.

The increases in the total weight of each of the various satellites associated with enhancement of the
seven years are presented graphically in Figs. 12 through 14. The first of these figures, in its three sections, affords comparison between the baseline (monopropellant hydrazine) small category satellite and each of the like category satellites that have either all electric propulsion subsystems or hybrid subsystems that employ both electric and hydrazine thrusters. Fig. 13 and Fig. 14 afford comparisons among satellites in the medium size category and in the large size category, respectively.

In each of the above cited charts, the line designated No. 1 traces the increase in the total weight of a satellite with a monopropellant hydrazine propulsion subsystem as the MMD of the satellite is enhanced from 3 years to 7 years. This curve serves as the baseline with which the increases in the weight of all of the other satellites are compared.

To assist in the interpretation of weight data, a broken horizontal line is drawn through the lowest point on the baseline curve in each chart. The point at which the broken horizontal line intersects the curve representing a specified type of satellite shows the number years to which the MMD of the satellite can be extended without incurring a weight penalty compared with the baseline satellite. For instance, in Fig. 12, the horizontal line intersects Curve No. 5 at 4.6 years, read from the scale on the abscissa. This indicates that employment of the hybrid mercury propellant subsystem in a small category satellite would make available the additional weight that is required to

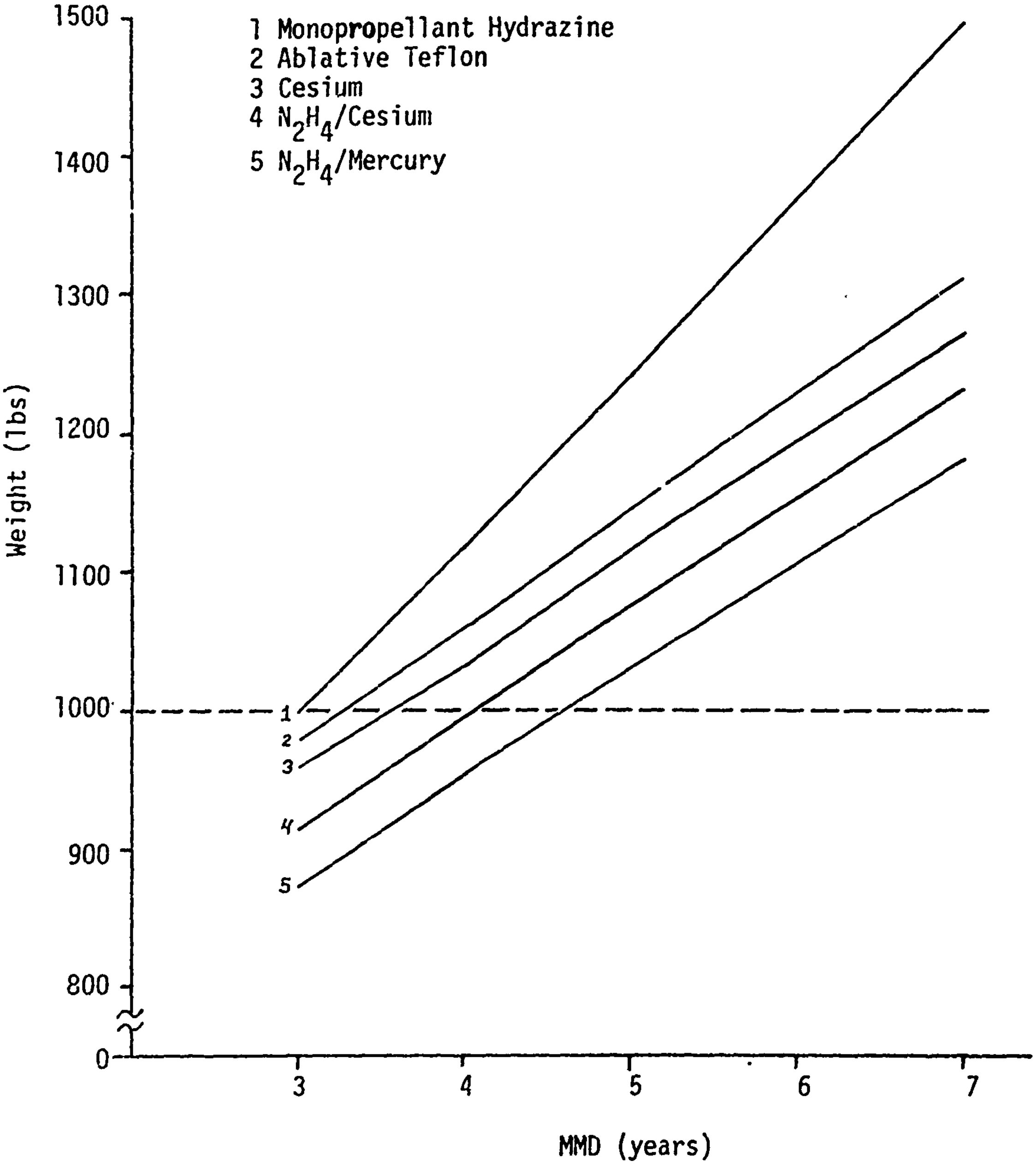

Fig. 12 Weight of Satellite as a Function of Type of Propulsion Subsystem and Mean Mission Duration - Small Category Satellites

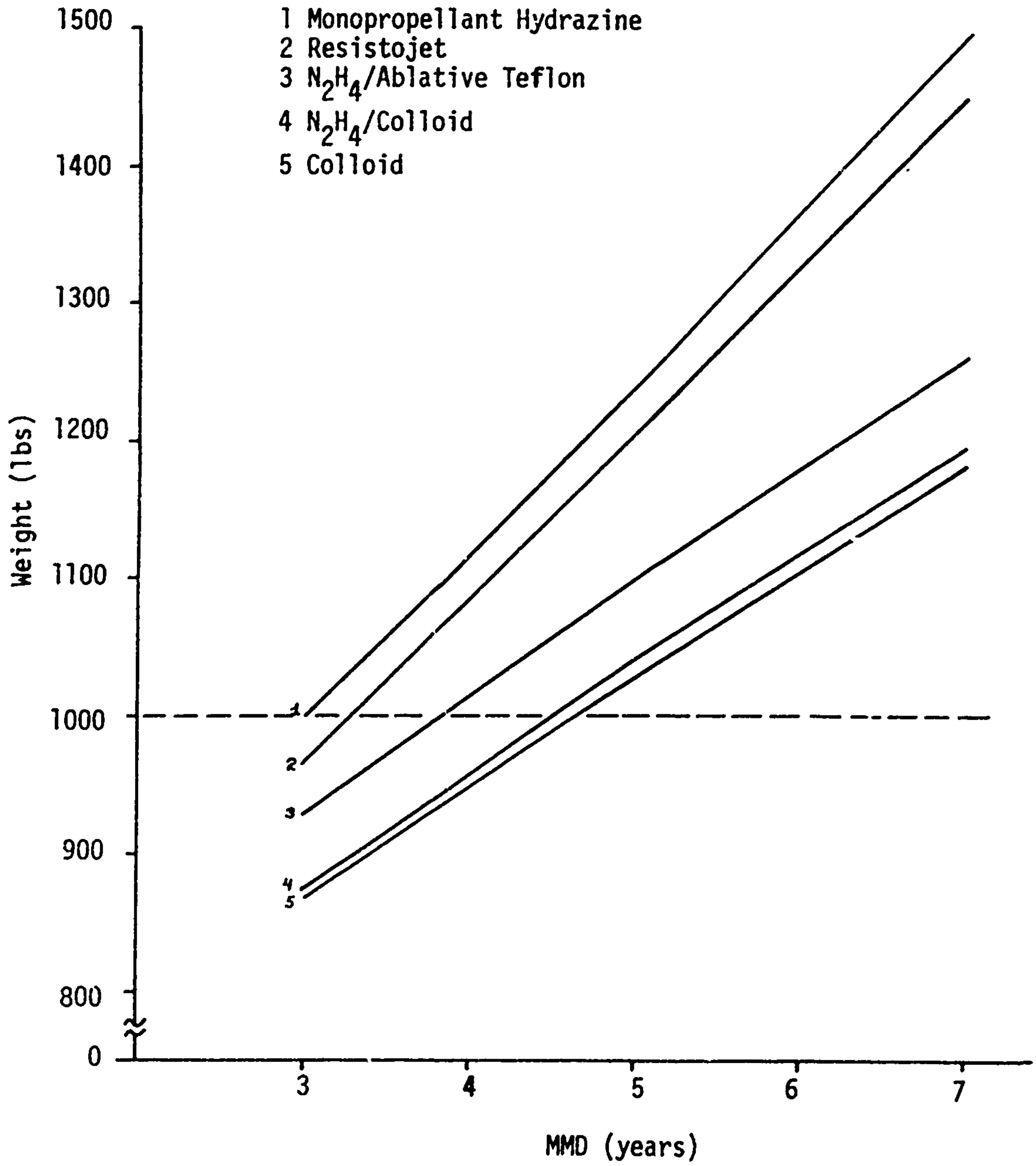

Fig. 12 (continued)

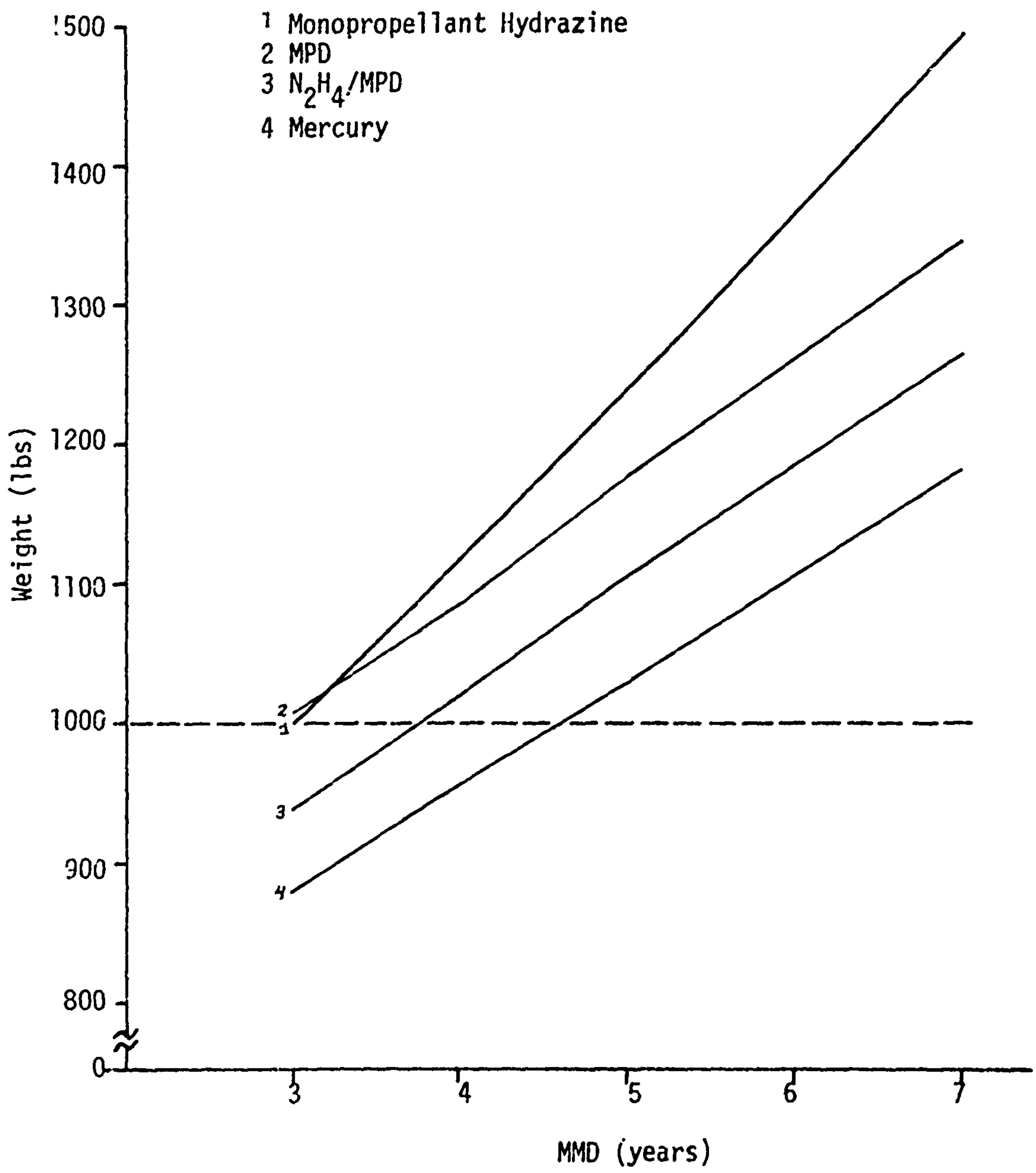

Fig. 12 (continued)

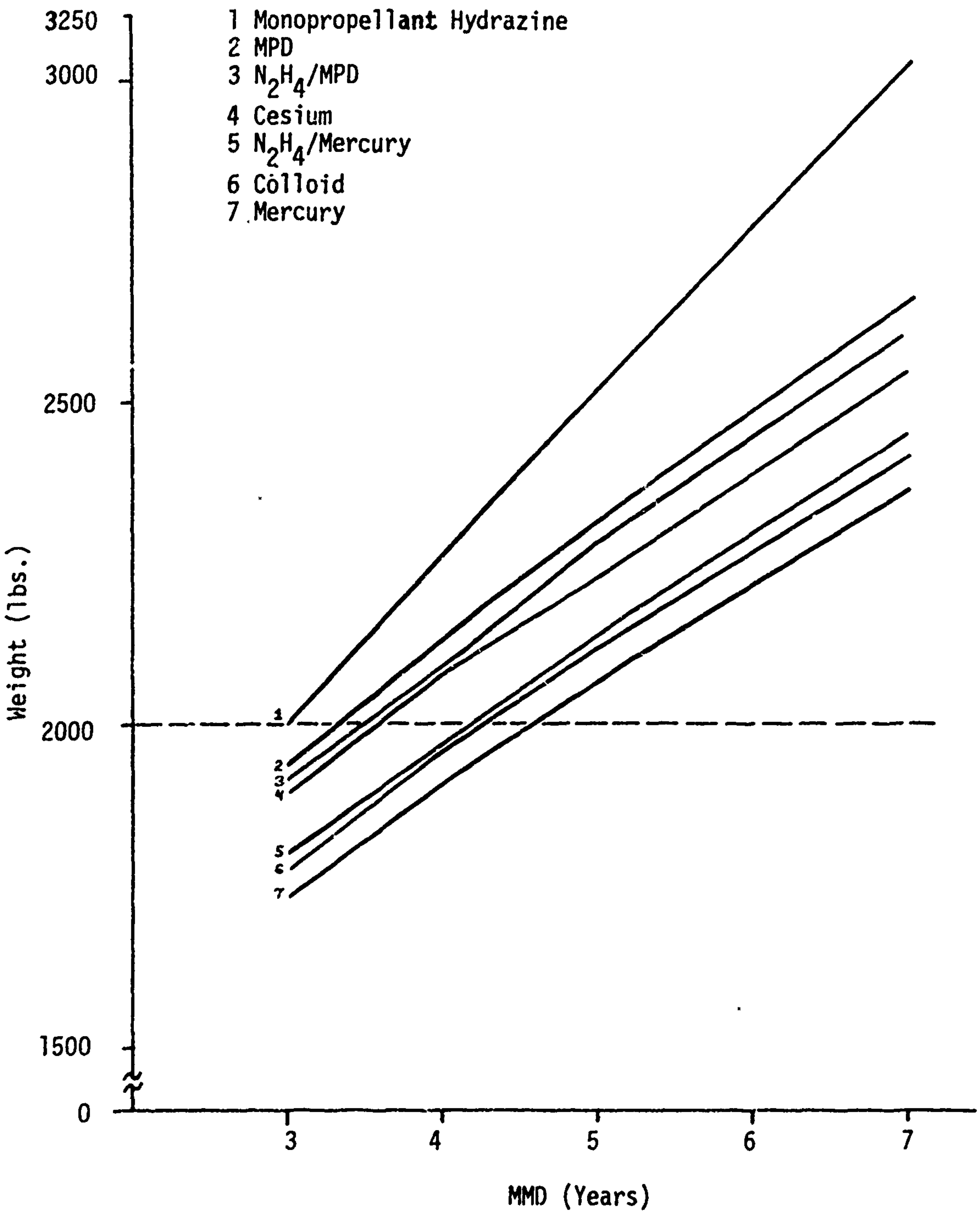

Fig. 13 Weight of Satellites as a Function of Type of Propulsion Subsystem and Mean Mission Duration - Medium Category Satellites

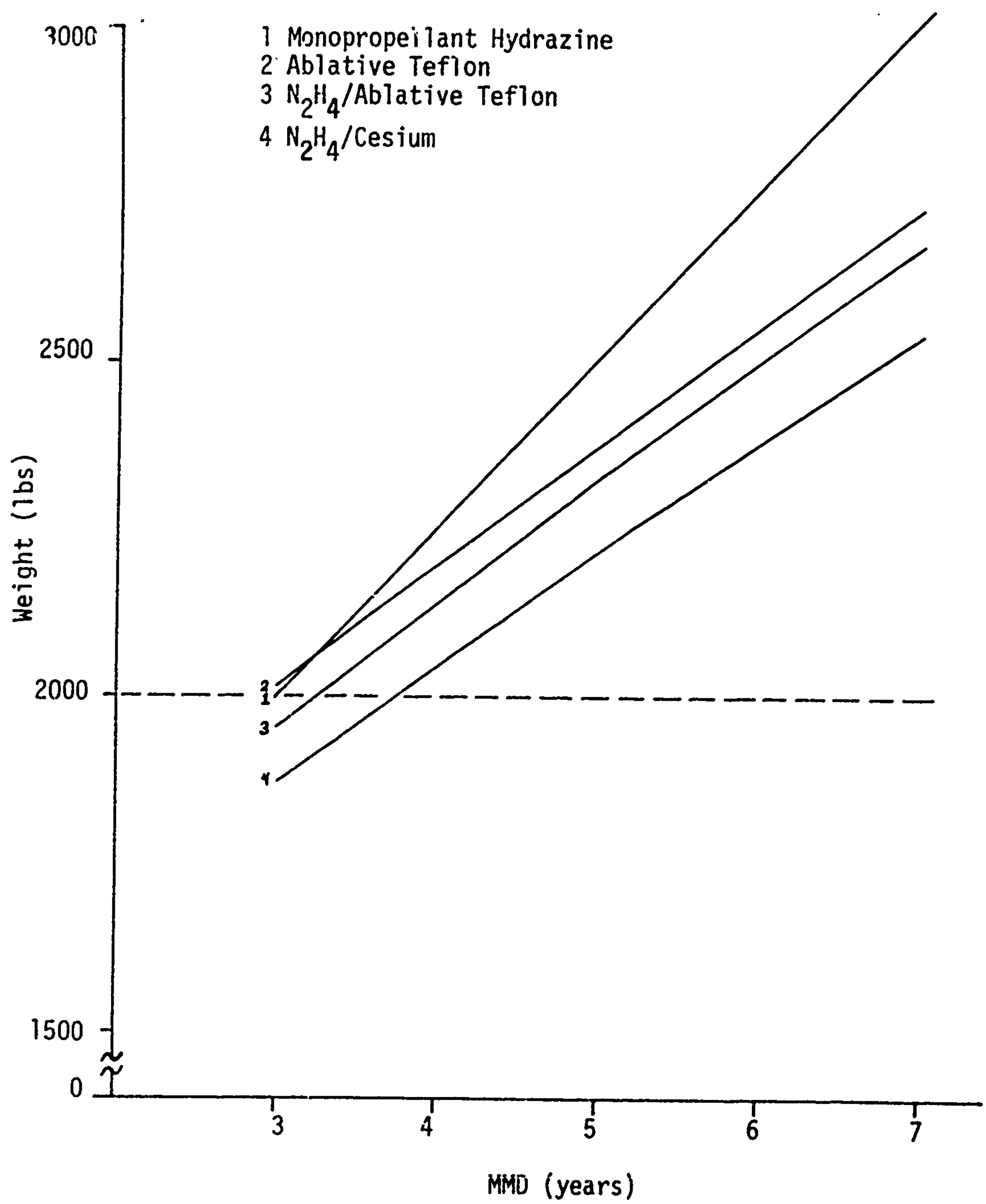

Fig. 13 (continued)

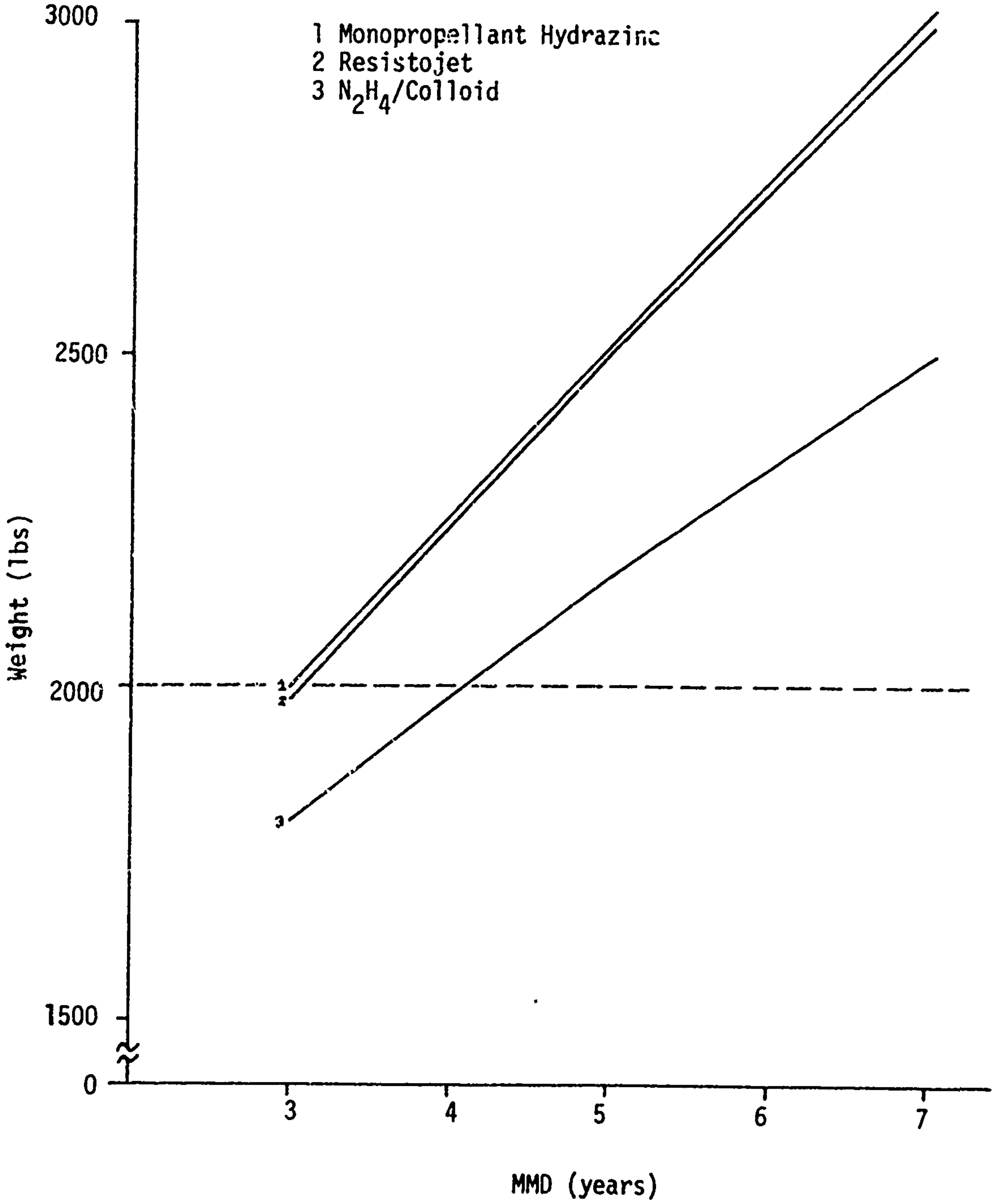

Fig. 13 (continued)

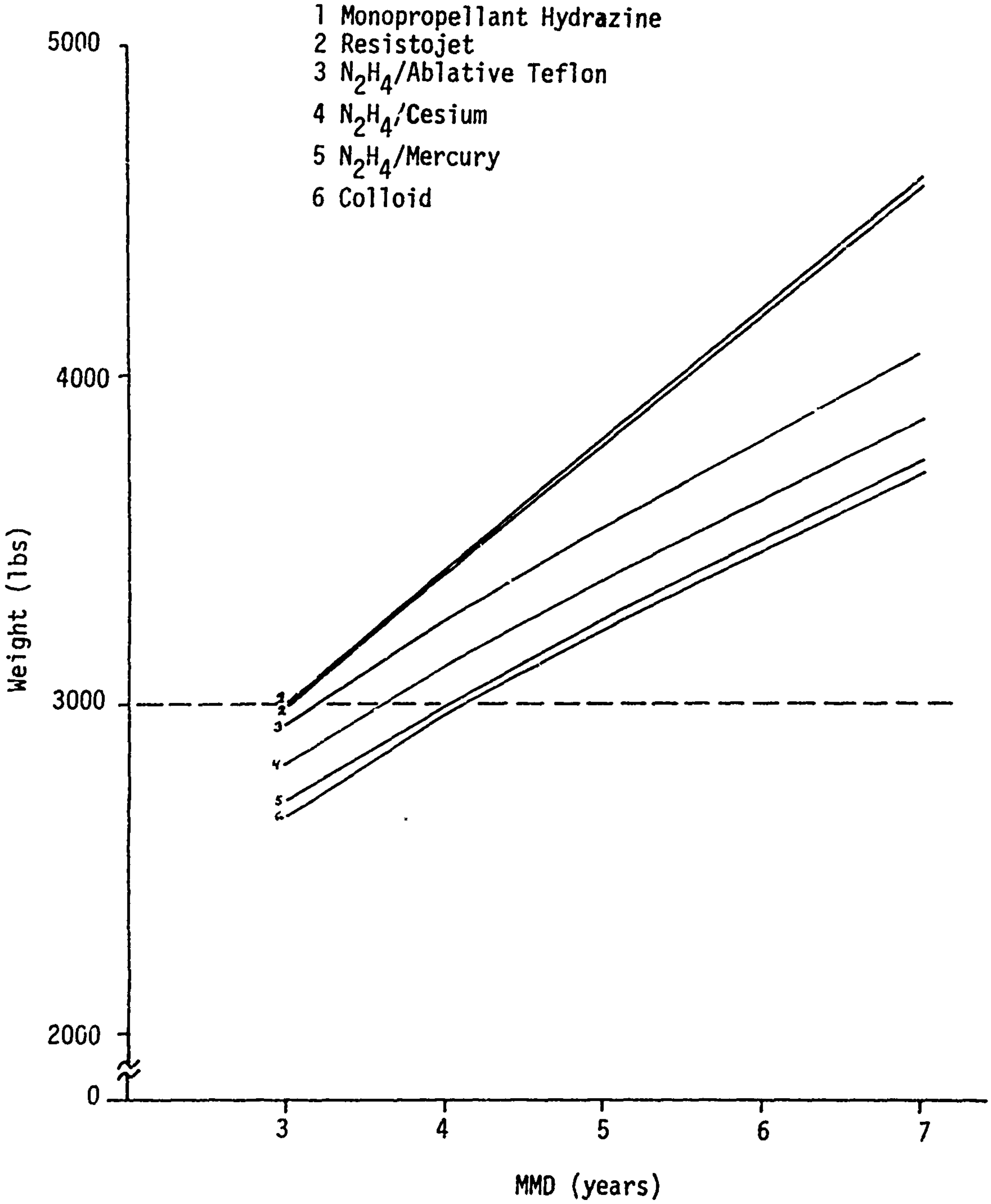

Fig. 14 Weight of Satellites as a Function of Type of Propulsion Subsystem and Mean Mission Duration - Large Category Satellites

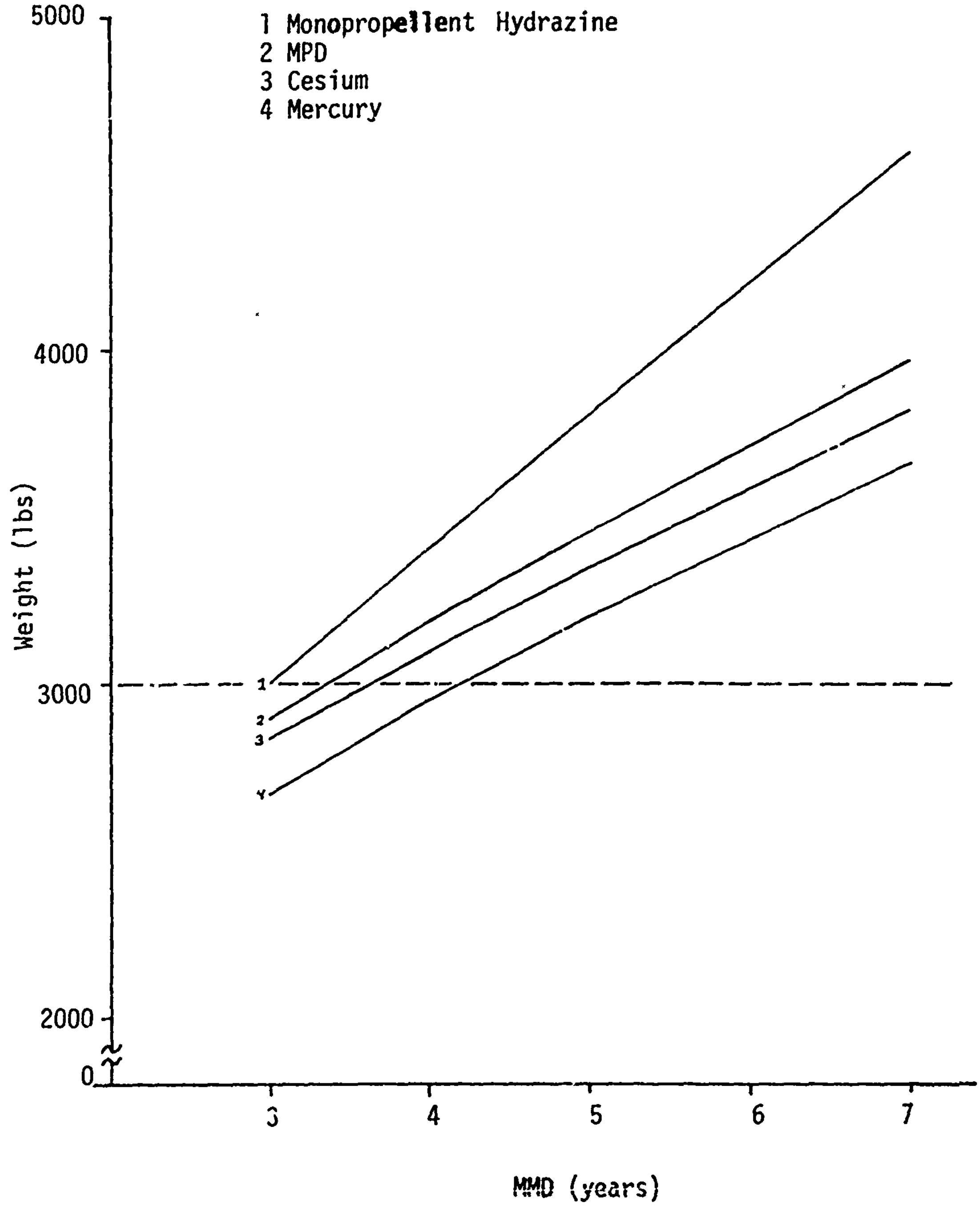

Fig. 14 (continued)

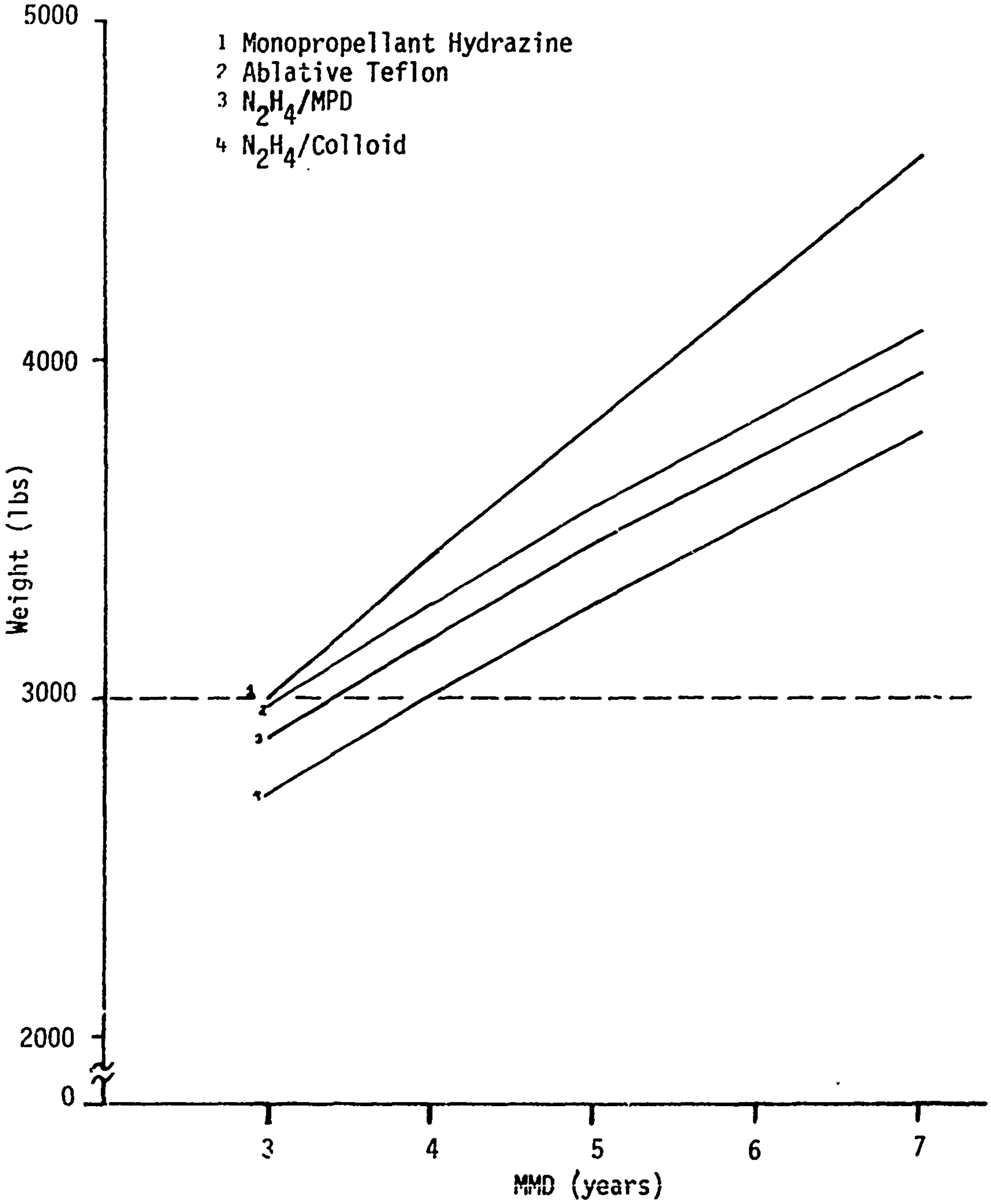

Fig. 14 (continued)

extend the MMD of the satellite from 3 years to 4.6 years. In contrast, use of the ablative teflon propulsion subsystem would provide for an enhancement of less than 0.3 years in the MMD of the satellite. Comparable conclusion regarding the enhancement of the MMD of a satellite that would be made possible by the employment of any of the eleven types of propulsion subsystems, in each satellite weight category, can be drawn from t! appropriate curve in Fig. 12, Fig. 13 or Fig. 14.

To determine the changes in the total weight of the satellites depicted in the accompanying charts, it was necessary to estimate the change in the weight of each major subsystem that would result from the use of electric propulsion in lieu of the conventional hydrazine subsystem. As shown in Table 5 in Section V, use of electric thrusters results in a substantial decrease in the weight of the attitude control subsystem because, primarily, of the lower weight requirement for propellants. This weight saving is offset in part by the increase in the weight of the solar panels and other elements of the electric power source subsystem. For a satellite with a specified MMD and mission, the structure weight is lighter if electric propulsion is employed, but the weights of the mission related subsystems (TT & C and communications) are constant. These differences in subsystem weights are illustrated by the data in Table 8. The table also shows the extent to which the total weight of a 3-year small category satellite is reduced by the use of the hybrid mercury propulsion subsystem, namely, from 1000 pounds to 875 pounds. This weight saving permits the MMD of the satellite with hybrid mercury propulsion to be extended from 3 years to 4.6 years without exceeding 1000 pounds, the weight of the baseline satellite. The increase in the weight of the communications subsystem from 219 pounds to 280 pounds provides for the additional redundancy in mission

TABLE 8

SATELLITE WEIGHT AS A FUNCTION OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

(Weight in pounds)

Satellite Subsystem	Satellite with Monopropellant Hydrazine Propulsion Subsystem	Satellite with Hybrid Mercury Propulsion Subsystem	
	3-Year MMD	3-Year MMD	4.6-Year MMD
Structure	211.5	184.9	202.6
TT and C	70.0	70.0	73.7
Communications	219.0	219.0	280.0
Electric Power:			
Distribution & Control	100.0	107.0	108.9
Batteries	88.5	94.7	96.1
Solar Panels	42.6	45.6	46.0
Attitude Control:			
Tanks	12.3	2.7	3.3
Other Dry Weight	117.1	115.1	138.9
Propellants	135.9	35.5	49.8
Pressurization	3.1	0.5	0.7
Satellite Total Weight	1,000.0	875.0	1,000.0

equipment that is essential to the extension of the MMD of the satellite.

In Section VIII, which follows, the significance of the potential extension in the useful life (MMD) of satellites is appraised in terms of the resultant reduction in 10-year satellite system costs.

3. COMPARATIVE WEIGHT SAVINGS

Since interest in the present study centers upon the saving in weight that could be realized through application of electric propulsion, the six propulsion subsystems that resulted in the largest weight savings in each satellite size category are listed in Table 9. The propulsion subsystems are ranked in order of saving in the over-all weight of the satellite. Satellites that employ colloid or mercury propulsion subsystems, without the use of any hydrazine, are generally lighter than those that utilize hybrid propulsion subsystems. Application of colloid or mercury also results in weight savings compared with the use of cesium, ablative teflon or MPD.

The use of hybrid mercury propulsion subsystem, although slightly heavier than all mercury or all colloid subsystems, shows slight weight advantages compared with other hybrid systems. However, the difference in weight between the N_2H_4/Mercury and the N_2H_4/Colloid is not large, typically only a few pounds. In one instance, namely, the 3-year small category satellites, the total weight of the two hybrids is the same. Only in the larger, longer life satellites does the difference between these two hybrid subsystems exceed forty pounds per satellite.

TABLE 9

SATELLITES WITH ELECTRIC PROPULSION SUBSYSTEMS
RANKED IN ORDER OF SAVING IN WEIGHT

Small Category Satellites:

Rank	3-Year MMD	4-Year MMD	5-Year MMD	7-Year MMD
1	Colloid	Colloid	Colloid	Mercury
2	N_2H_4/Mercury[a]	N_2H_4/Mercury	N_2H_4/Mercury	N_2H_4/Mercury
3	N_2H_4/Colloid[a]	Mercury	Mercury	Colloid
4	Mercury	N_2H_4/Colloid	N_2H_4/Colloid	N_2H_4/Colloid
5	N_2H_4/Cesium	N_2H_4/Cesium	N_2H_4/Cesium	N_2H_4/Cesium
6	N_2H_4/Teflon	N_2H_4/Teflon	N_2H_4/Teflon	N_2H_4/Teflon

Medium Category Satellites:

Rank	3-Year MMD	4-Year MMD	5-Year MMD	7-Year MMD
1	Mercury	Mercury	Mercury	Mercury
2	Colloid	Colloid	Colloid	Colloid
3	N_2H_4/Mercury	N_2H_4/Mercury	N_2H_4/Mercury	N_2H_4/Mercury
4	N_2H_4/Colloid	N_2H_4/Colloid	N_2H_4/Colloid	N_2H_4/Colloid
5	N_2H_4/Cesium	N_2H_4/Cesium	N_2H_4/Cesium	N_2H_4/Cesium
6	Cesium	Cesium	Cesium	Cesium

Large Category Satellites:

Rank	3-Year MMD	4-Year MMD	5-Year MMD	7-Year MMD
1	Colloid	Mercury	Mercury	Mercury
2	Mercury	Colloid	Colloid	Colloid
3	N_2H_4/Mercury	N_2H_4/Mercury	N_2H_4/Mercury	N_2H_4/Mercury
4	N_2H_4/Colloid	N_2H_4/Colloid	N_2H_4/Colloid	N_2H_4/Colloid
5	Cesium	Cesium	Cesium	Cesium
6	N_2H_4/Cesium	N_2H_4/Cesium	N_2H_4/Cesium	N_2H_4/Cesium

(a) Weight of the two hybrids is the same, namely, 875 pounds.

SECTION VIII

SATELLITE SYSTEM COSTS

1. NATURE AND SCOPE OF SYSTEM COSTS

The system cost associated with any satellite consists of two major categories, namely, the cost of the satellite per se and the cost of the launch vehicle used to place the satellite in orbit. Within each of these two categories, nonrecurring costs are distinguished from those that are directly related to the launching of particular satellites. The latter costs include both hardware and operation costs and are referred to as recurring costs. The nonrecurring items include RDT & E costs, the cost of the aerospace ground equipment, and all other investment costs that would be incurred regardless of the number of satellites deployed.

All costs in the present analysis are stated in terms of 1973 dollars. The allowances made for cost escalation from 1970 to 1973 are based on a study made by the Space and Missile Systems Organization (SAMSO), Ref. 8.

2. SATELLITE COSTS

The satellite subsystem weights discussed in the preceding section and the power requirements cited in Section V were used as inputs in estimating satellite costs. A cost model was developed and computerized. The cost estimating relationships (CERs) used in estimating costs associated with each of the major subsystems of the satellites, except those incorporating electric thrusters and related elements, were derived from the Unmanned Spacecraft Cost Model developed by the AFSC Space and Missile Systems Organization (SAMSO), Refs. 9 and 10. The CERs for electric propulsion subsystem thrusters, propellant tanks, propellants, and power conditioning were developed from information obtained from Headquarters National Aeronautics and Space Administration

(NASA), Goddard Space Flight Center and Jet Propulsion Laboratory. The CERs and related cost factors that were incorporated in the computerized cost model are listed in Appendix C. In addition, the complete computer program is reproduced in the appendix.

The computerized cost model generates and summarizes all nonrecurring costs associated with the development and testing of each satellite and the first unit cost of each satellite. These two basic figures for small category satellites with each of the twelve types of propulsion subsystems and selected MMD periods are given in Tables D1 and D2 in Appendix D. Comparable estimates for medium category satellites are entered in Tables D3 and D4 and for large category satellites in Tables D5 and D6 in the same appendix.

The first table in each of the pairs of tables cited above provides cost estimates for a constellation of 6 satellites in orbit whereas the second table in each set provides comparable estimates for a constellation of 12 satellites in orbit. The satellite nonrecurring cost and the first unit cost for each type of satellite are identical in the two tables because these two basic figures are independent of the number of satellites deployed. Calculation of the cumulative average cost of the number of satellites required for different size constellations of satellites is illustrated in Table 10. The basic data are taken from the first line of Tables D1 and D2 in Appendix D. Appendix Tables D1 through D18 provides comparable estimates for each type of satellite and MMD period considered in this report.

The number of satellites required to establish and maintain each of the constellations of satellites in orbit for ten years was computed from the data and chart in Ref. 7, pages 4-33 and 4-34. The data are presented graphically in Fig. 15 for convenient reference.

TABLE 10

COST OF SMALL CATEGORY SATELLITES WITH MONOPROPELLANT HYDRAZINE PROPULSION SUBSYSTEMS AND 3-YEAR MMD

(Costs in thousands of 1973 dollars)

Number of Satellites and Type of Cost	Constellation of 6 Satellites		Constellation of 12 Satellites	
	Detail	Total	Detail	Total
Number of Satellites Required in 10-Year Period	25		50	
Nonrecurring Cost		55,860		55,860
Recurring Cost:				
First Unit Cost	11,770		11,770	
Cumulative Average Cost	9,932[a]		9,470[b]	
Total Recurring Cost		248,300		473,500
Total 10-Year Satellite Cost		304,160		529,360

(a) Computed by multiplying the first unit cost by the learning curve factor 0.8438.
(b) Computed by multiplying the first unit cost by the learning curve factor 0.8045.

The learning curve factors applied to the first unit cost of each satellite to determine the cumulative average unit cost (Table 10 and elsewhere) are taken from a learning curve with a 95 percent slope (Ref. 11).

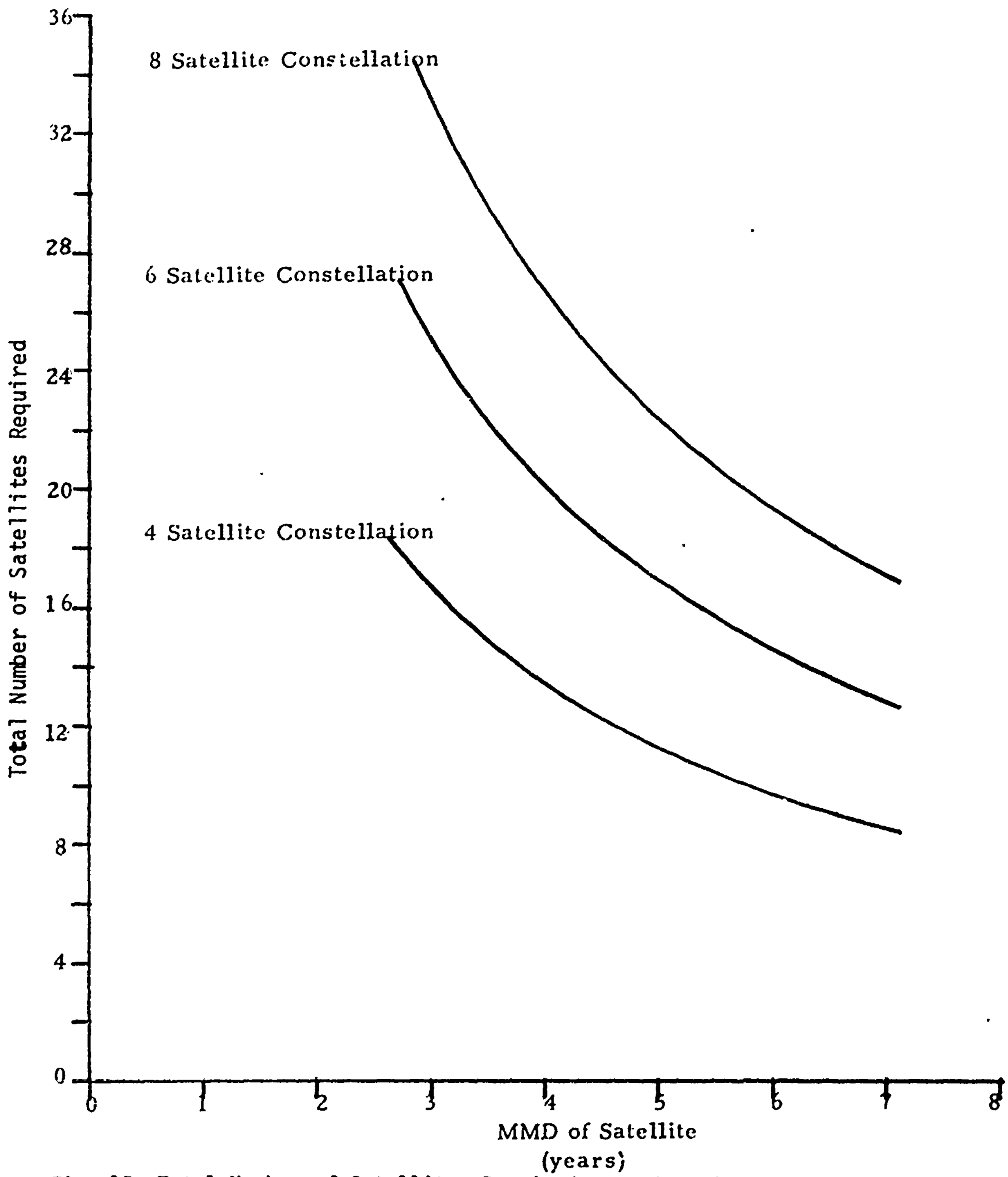

Fig. 15 Total Number of Satellites Required as a Function of the Mean Mission Duration of the Satellite

3. LAUNCH VEHICLE COSTS

The launch vehicle costs were determined in consultation with the SAMSO Launch Vehicle Requirements and Analysis Office. The unit recurring costs for nine selected launch vehicles are shown in Table 11. Each of these recurring costs represents the anticipated cost per launch of the specified vehicle based on the quantity that is likely to be required for all purposes. The unit recurring costs consist of the hardware (production) cost of the launch vehicle and the operating cost incident to launching the vehicle.

The nonrecurring costs comprise the cost of developing and testing the indicated combination of launch elements, together with the cost of modification of structures or enhancement of capabilities when required. The nonrecurring cost of the Atlas/Agena, estimated at $1.6 million in 1973 dollars, would be required to provide a 10-foot front end for the vehicle. The combination of the Agena with the Titan IIID would involve a developing and testing cost estimated at $6.0 million. Enhancement of the capabilities of the Agena would require an additional $3.5 million in R & D funds, but the unit production cost of the Improved Agena would be approximately the same as that of the present Agena, namely $20.0 million. Addition of an attitude kick motor (AKM) to the Titan IIID/Agena combination would increase the nonrecurring costs by about $4.0 million and the unit recurring cost by $1.0 million. The satellite weight that each of the launch vehicles could place in synchronous equatorial orbit is listed in Table 11, along with the related cost data.

The launch vehicle that would be used depends upon the weight of the individual satellite or of a combination of satellites. Since the weights of the small category satellites range from 1000 pounds to 1496 pounds, it is postulated that two of these satellites would be launched aboard a Titan IIIC

TABLE 11

CAPABILITIES AND ESTIMATED COST OF SELECTED LAUNCH VEHICLES

Launch Vehicle (LV)	Gross Weight in Synchronous Equatorial Orbit (lbs)	Satellite Weight Range(a) (lbs)	Launch Vehicle Cost (Millions of 1973 dollars) Non-recurring Cost	Unit Recurring Cost
SLV-3A (Atlas)/Agena	610	(b)	1.6	11.6
Titan IIIB/Agena	1400	(b)	0.0	13.7
SLV-3D/Centaur/Burner II	1900	(b)	0.0	15.2
Titan IIIC	3200	Up to 3141	6.0	20.0
Titan IIID/Improved Agena	4350	3791 - 4275	9.5	20.0
Titan IIID/Agena/AKM	4875	4276 - 4795	10.0	21.0
Titan IIID/Imp. Agena/AKM	5100	4796 - 5015	13.5	21.0
Titan IIIE Centaur	7200	(b)	0.0	25.2

(a) Based on one satellite per launch. If two satellites are launched by one LV, the net weight range is reduced by 20 pounds.

(b) Not determined because the LV was not used in estimating system cost.

launch vehicle. The medium category satellites weight between 2000 and 3016 pounds, and therefore, only one of the medium size satellites could be placed in synchronous equatorial orbit by a Titan IIIC. Inasmuch as all satellites in the small and medium size categories would be launched aboard Titan IIIC vehicles, the cost of launching such satellites is calculated by multiplying the average unit cost of the Titan IIIC, namely, $19.5 million (Table 11), by the number of launch vehicles required. No nonrecurring costs are incurred in the launching of a Titan IIIC because the vehicle is currently operational.

The large category satellites range in weight from 3000 to 4591 pounds. For satellites with a net weight of more than 3140 pounds, a launch vehicle combination would need to be developed that would be efficient in placing the selected large category satellite in synchronous equatorial orbit. Possible combinations of launch vehicles, together with their rated capabilities and associated costs, are listed in Table 11. The launch costs for large category satellites used throughout this report and shown in detail in Appendix D, Tables D5, D6, D11, D12, D17 and D18, were computed from the data in Table 11.

4. SATELLITE SYSTEM COSTS

The over-all cost of a satellite system is the summation of the costs associated directly with the satellites and all costs incident to the launching of the satellites. In this report, all system costs are based on the assumption that the constellation of satellites would be placed and maintained in synchronous equatorial orbit for a period of ten years.

The procedure followed in summarizing satellite system costs is illustrated in Tables 12 and 13, Section IX, which compare the 10-year costs of small category satellites using hybrid mercury propulsion subsystems with the corresponding costs of the baseline satellites that use monopropellant hydrazine.

SECTION IX

ANALYSIS AND RESULTS

1. INTRODUCTION

Two areas in which potential contributions of the application of electric propulsion have been evaluated are discussed in the major subsections which follow. The two areas are (a) enhancement of the mean mission duration (MMD) of the satellite and (b) increased flexibility with respect to the design weight of a satellite and the selection of launch vehicles to place satellites in intermediate earth orbits.

2. ENHANCEMENT OF LIFE OF SATELLITES

a. Objective. The purpose of this major subsection of the report is to estimate the potential savings that would accrue from extending the MMD of the satellite. Each satellite under consideration is a member of a constellation of satellites in synchronous equatorial orbit. The satellite requires initial positioning, attitude control, east-west and north-south stationkeeping, and repositioning. Five types of satellites employing electric propulsion exclusively and six types of satellites with hybrid propulsion subsystems are compared with satellites that employ monopropellant hydrazine propulsion subsystems and have an MMD of 3 years.

b. System Cost of Small Category Satellites with Hybrid Mercury Propulsion. Of the ten types of satellites that incorporate some form of electric propulsion, the type that employs the hybrid mercury propulsion subsystem is selected for detailed presentation. Hybrid propulsion is preferred because the availability of high thrust engines along with those with low thrust increases the operational flexibility of the satellite. The hybrid mercury subsystem is selected because it shows slight weight advantages compared with the other hybrid subsystems under study (See Section VII, 3).

System cost estimates for the types of satellites not discussed in this subsection are shown in Table D1 through D18 in Appendix D. The extent to which the 10-year system cost of each type of satellite declines as the MMD of the satellite is enhanced is presented graphically in Figs. 1 through D6 in the same appendix. The data presented in Tables 12 and 13, were extracted from Appendix Tables D1, D2, D7, and D8.

Fig. 12 in the satellite weight analysis section shows that employment of the hybrid mercury propulsion subsystem in lieu of the baseline hydrazine subsystem would make provision for the additional weight required to extend the MMD of a small category satellite from 3 years to 4.6 years. The significance of this enhancement in the life of the satellite is appraised in terms of the saving in 10-year system costs in the tables and text which follow.

In Table 12, the 10-year systems cost of a constellation of 6 satellites with hybrid mercury propulsion is compared with the 10-year cost of a like constellation of satellites with a monopropellant hydrazine propulsion subsystem. The system costs comprise estimates of the cost of developing, qualifying and producing the satellites together with the cost of launching the satellites and maintaining the constellation in orbit during a period of 10 years.

The cost comparison presented in Table 12, based on a constellation of 6 satellites, indicates that enhancement of the MMD of the satellite from 3 to 4.6 years made possible by the use of hybrid mercury propulsion would result in an estimated saving of $99 million which is 18 percent of the 10-year cost of conventional satellites with hydrazine propulsion. This indicated saving in total system cost results directly from the reduced number of satellites (18 vs 25) and launch vehicles (9 vs 12.5) that are required to maintain

TABLE 12

COMPARATIVE COSTS FOR CONSTELLATIONS OF SIX SMALL CATEGORY SATELLITES IN ORBIT DURING TEN YEAR PERIOD

(Costs in thousands of 1973 dollars)

Cost Element	Satellite with Monopropellant Hydrazine Propulsion Subsystem 1000 lbs., 3-Yr. MMD			Satellite with Hybrid Mercury Propulsion Subsystem 1000 lbs., 4.6-Yr. MMD			Potential Cost Reduction	
	No.	Unit Cost	Total Cost	No.	Unit Cost	Total Cost	Amount	Percent
Satellite Cost								
Nonrecurring Cost			55,860			76,990		
Recurring Cost	25.0	9,932	248,300	18	10,919	196,540		
Total Satellite Cost			304,160			273,530	30,630	10.1
Launch Cost								
Nonrecurring Cost			-0-			-0-		
Recurring Cost	12.5	19,500	243,750	9	19,500	175,500	68,250	28.0
Total 10-Yr. System Cost			547,910			449,030	98,880	18.0

a given capability over a 10 year period rather than from lower unit costs. In fact, both nonrecurring and unit recurring costs for the satellite with hybrid mercury propulsion subsystem are higher than the corresponding costs for the baseline satellite.

When the cost comparison between the two types of satellites is based on a constellation of 12 satellites, as shown in Table 13, the estimated reduction in total system cost amounts to $214 million, or 21 percent of the cost of the conventional system. Cost comparisons are presented for both the 6 satellite and the 12 satellite constellations primarily to show that the general conclusion regarding the potential cost saving applies to a wide range in the number of satellites deployed.

As indicated above, the potential savings cited in the two preceding paragraphs result from extension of the MMD of the satellite which is made possible by the use of hybrid mercury propulsion subsystems that make available the additional weight that is required to increase redundancy. Satellites typically have a few components or subsystems that have low reliability compared with other subsystems for which the predicted reliability is above 0.97. If volume and weight are available and redundancy is concentrated in the areas of low reliability, the MMD of the satellite will be enhanced. A comprehensive study made by the Aerospace Corporation (Ref. 7) shows that the redundancy technique would work for both the Program 191 and Program 777 satellites. It was found that the satellite life was increased by a factor of 3 by only doubling the number of components while satellite weight increased only 30 percent. Five components, however, exhibited wearout which affects lifetime (Ref. 7, page 2-2). Each of these components requires study to determine cost associated with attaining longer lifetime.

TABLE 13

COMPARATIVE COSTS FOR CONSTELLATIONS OF TWELVE SMALL CATEGORY SATELLITES IN ORBIT DURING TEN YEAR PERIOD

(Costs in thousands of 1973 dollars)

Cost Element	Satellite with Monopropellant Hydrazine Propulsion Subsystem 1000 lbs., 3-Yr. MMD			Satellite with Hybrid Mercury Propulsion Subsystem 1000 lbs., 4.6-Yr. MMD			Potential Cost Reduction	
	No.	Unit Cost	Total Cost	No.	Unit Cost	Total Cost	Amount	Percent
Satellite Cost								
Nonrecurring Cost			55,860			76,990		
Recurring Cost	50	9,470	473,500	36	10,420	375,120		
Total Satellite Cost			529,360			452,110	77,250	14.6
Launch Cost								
Nonrecurring			-0-			-0-		
Recurring Cost	25	19,500	487,500	18	19,500	351,000	136,500	28.0
Total 10-Yr. System Cost			1,016,860			803,110	213,750	21.0

In conclusion, it may be stated it is unlikely that the development cost involved in extending the lifetime of components subject to wearout, or the errors in cost estimation, would negate the savings that would result from the use of the hybrid mercury subsystem when the propulsion functions include stationkeeping.

c. Graphic Comparisons of System Costs for Small Category Satellites. Fig. 16 through Fig. 19 afford comparisons between the 10-year system cost of the small category satellite with monopropellant hydrazine propulsion and the like cost of each of the ten small category satellites that employ some type of electric propulsion including the hybrid mercury subsystem discussed above. Comparable data for the N_2H_4/Resistojet also are shown. From the first of the four charts, it will be observed that the satellites which employ either colloid or mercury propulsion subsystems without the use of hydrazine thrusters show lower 10-year systems cost than do any of the other propulsion subsystems under study. The systems cost of the satellite with hybrid mercury propulsion, however, is only slightly higher than that of the satellite with all mercury propulsion, namely, $449 million compared with $438 million for the all mercury subsystem. As previously mentioned, the hybrid mercury subsystem was selected for detail discussion because of its performance capabilities.

Fig. 17 presents comparisons among the various satellites in terms of percent reduction, or improvement, in the 10-year system costs. The horizontal line, designated "0", represents the 10-year cost of the baseline satellites, namely, $548 million.

Each of the above two charts relate to a constellation of 6 satellites in orbit. Fig. 18 and 19 afford similar comparisons among the twelve types

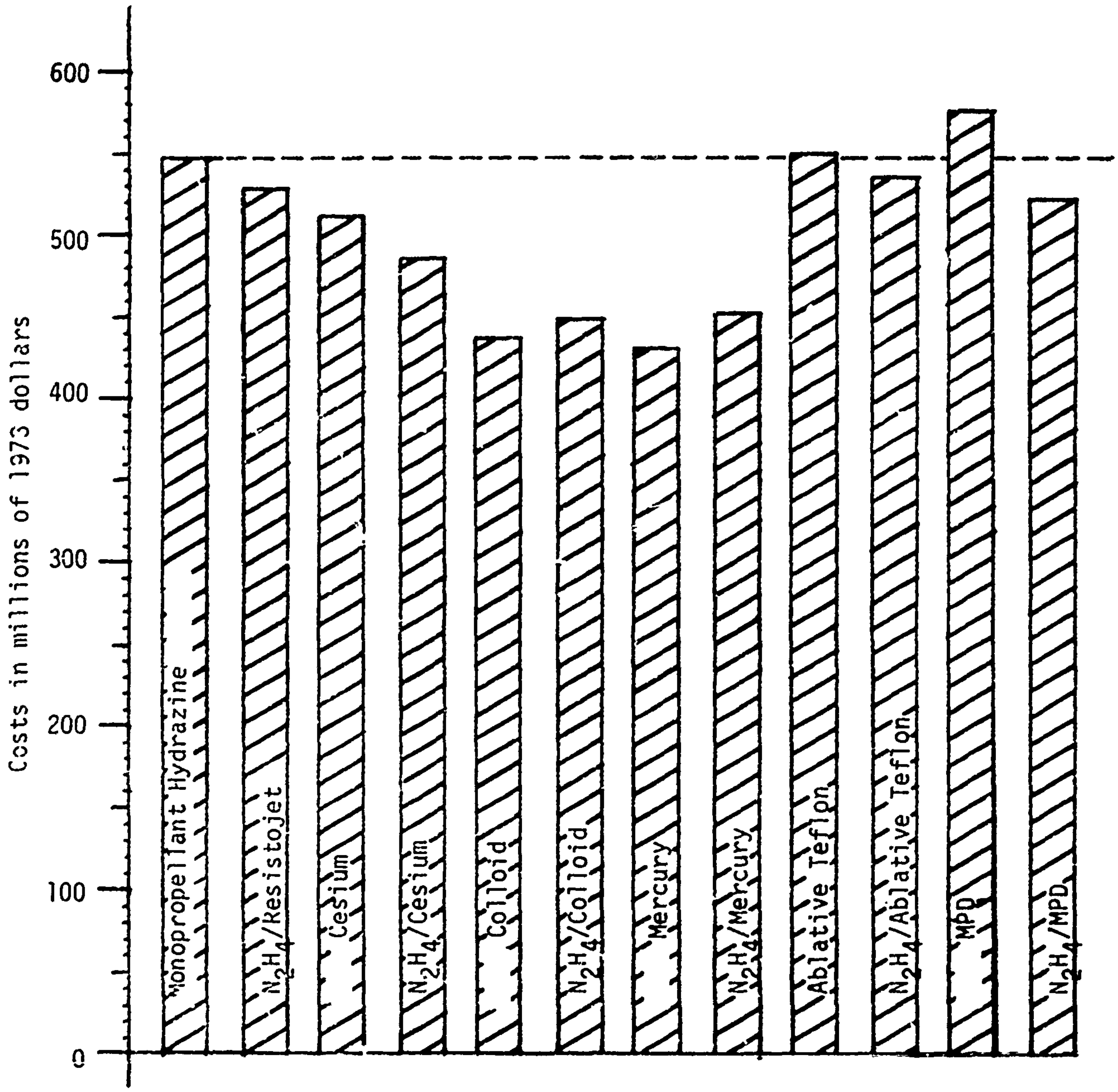

Fig. 16 Ten-Year System Cost of Constellations of Six Small Category Satellites with Specified Propulsion Subsystems

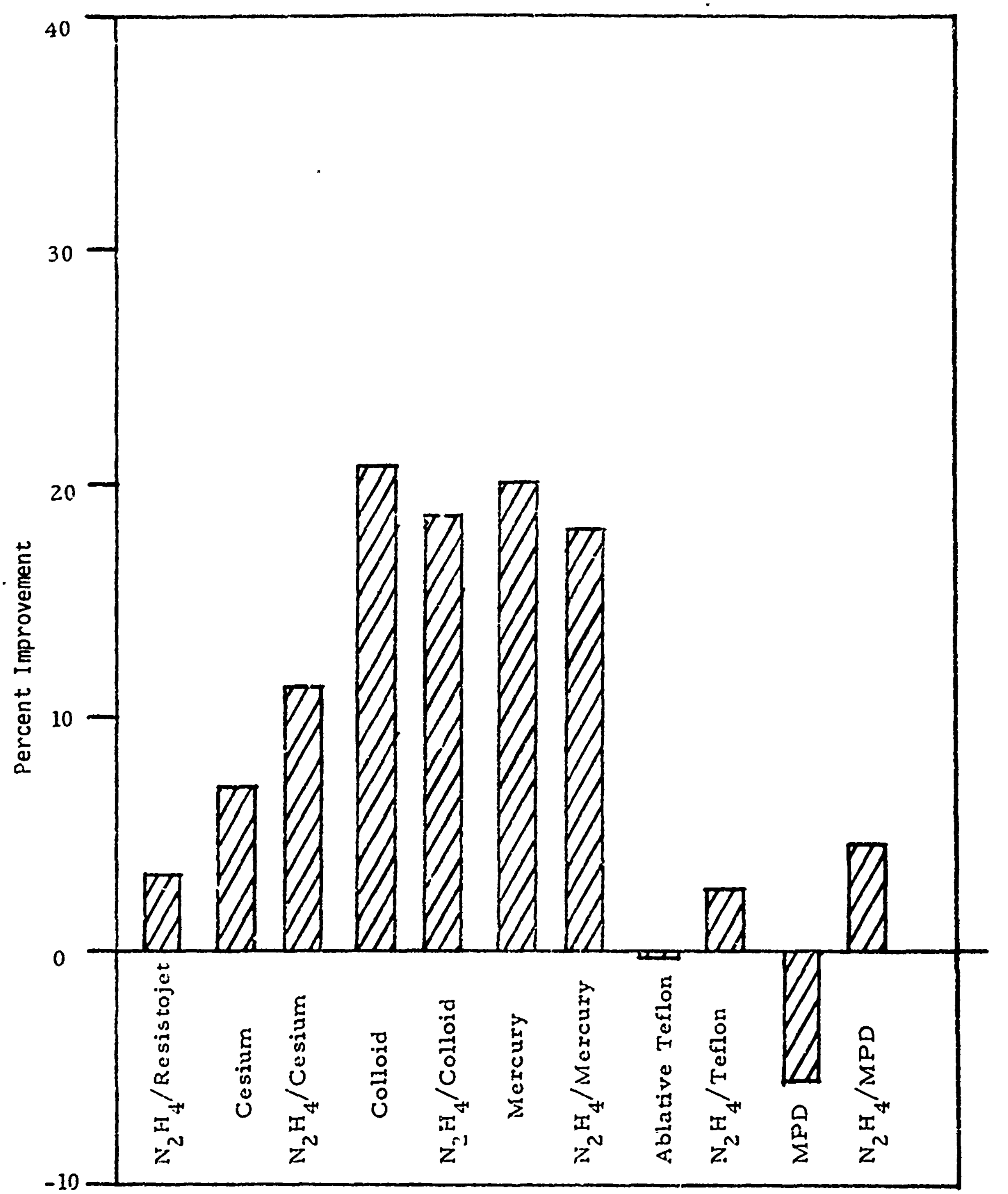

Fig. 17 Percent Reduction in Cost of Constellation of Six Small Category Satellites with Specified Propulsion Subsystems Compared with Baseline Satellite

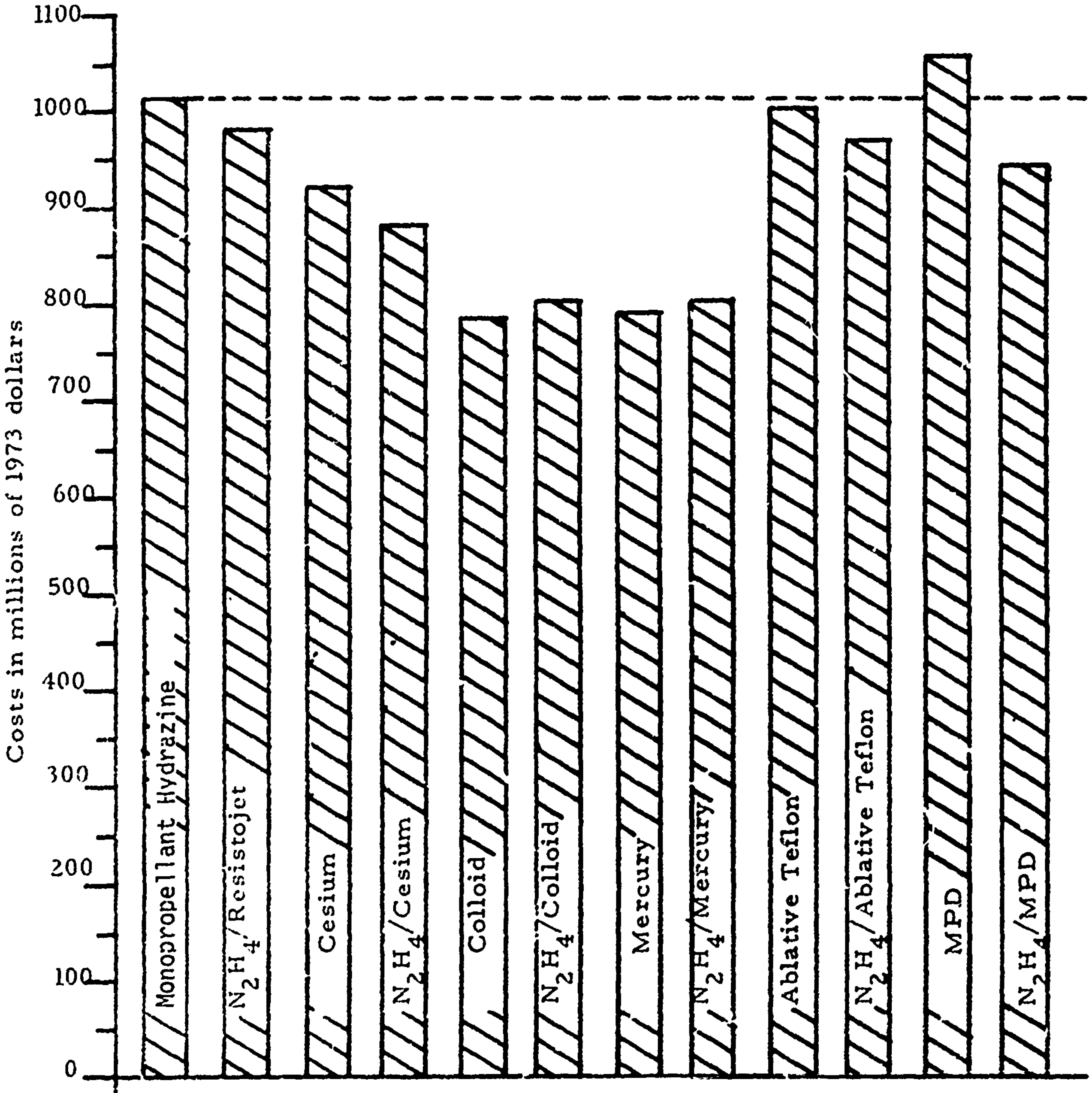

Fig. 18 Ten-Year System Cost of Constellations of Twelve Small Category Satellites with Specified Propulsion Subsystems

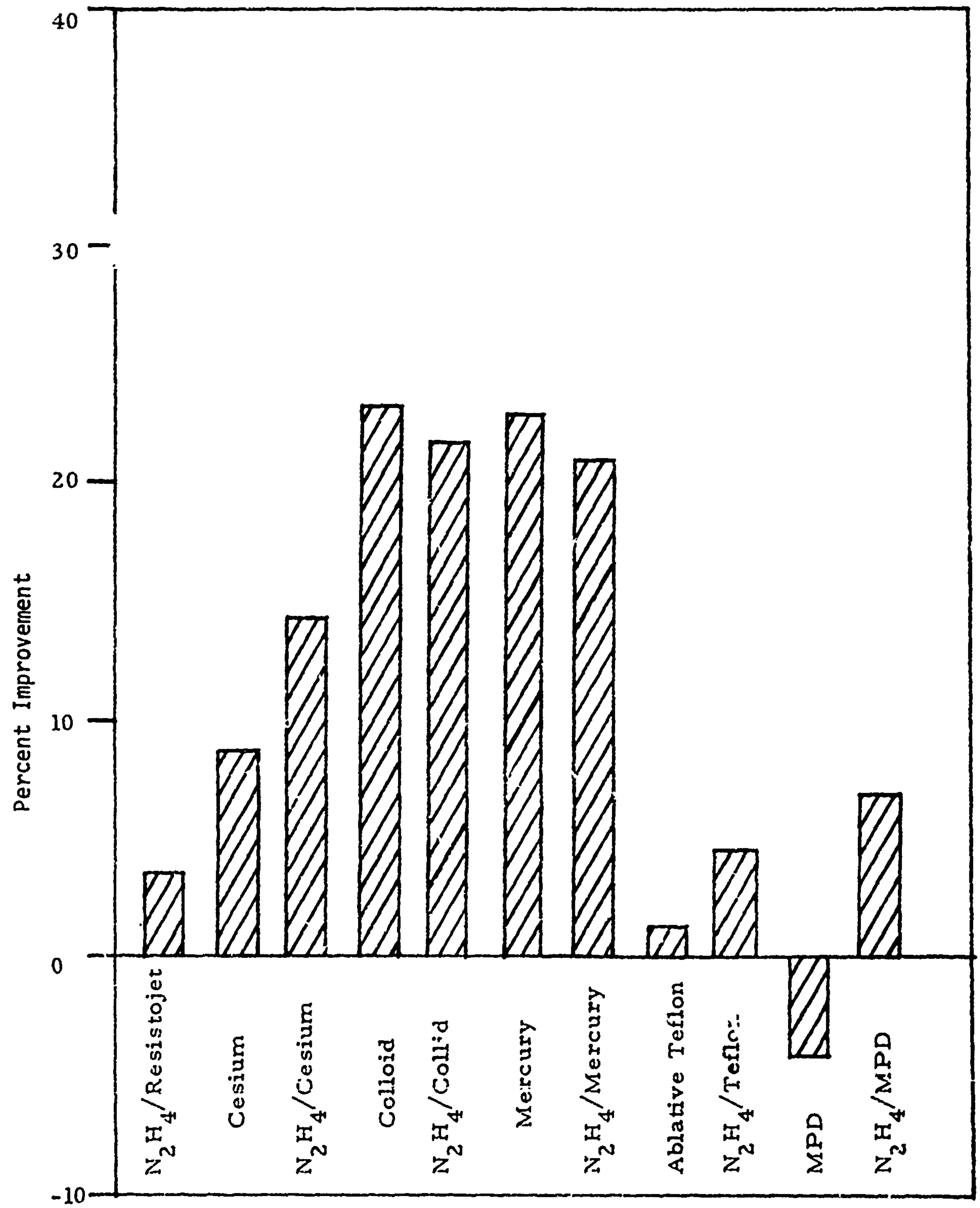

Fig. 19 Percent Reduction in Cost of Constellation of Twelve Small Category Satellites with Specified Propulsion Subsystems Compared with Baseline Satellite

of satellites based on the 10-year costs of constellations of 12 satellites in orbit. The percent reductions in systems costs are larger when based with the 12 satellite constellations because the relatively high nonrecurring costs of the satellite with electric propulsion are spread (amortized) over a larger number of satellites.

d. System Cost Comparisons for Medium Category Satellites. Fig. 19 through Fig. 22 present cost comparisons for satellites in medium size category which parallel those for small category satellites discussed in the preceding subsection.

In the medium category satellite, employment of the all mercury propulsion subsystem results in 10-year system costs that are distinctly lower than those of any of the other propulsion subsystem. Compared with the all colloid subsystem, the closest competitor from a cost standpoint, the all mercury subsystem shows a saving of nearly $26 million based on 6 satellites in orbit or $52 million based on a constellation of 12 satellites. Compared with the baseline hydrazine subsystem, mercury propulsion offers savings of $212 million and $432 million based on the 6 and 12 constellations, respectively. These system cost comparisons are taken from Tables D3 and D4 in Appendix D. These appendix tables provided the data from which the accompanying series of four charts were prepared.

The hybrid propulsion subsystems when incorporated in medium category satellites result in larger dollar savings but show smaller percentage reduction in system costs than when the hybrid mercury subsystem is employed in the small category satellites. For instance, employment of the hybrid mercury subsystem in a medium category satellite would result in a saving of $318 million, or 18 percent, compared with 10-year system cost of 12 baseline

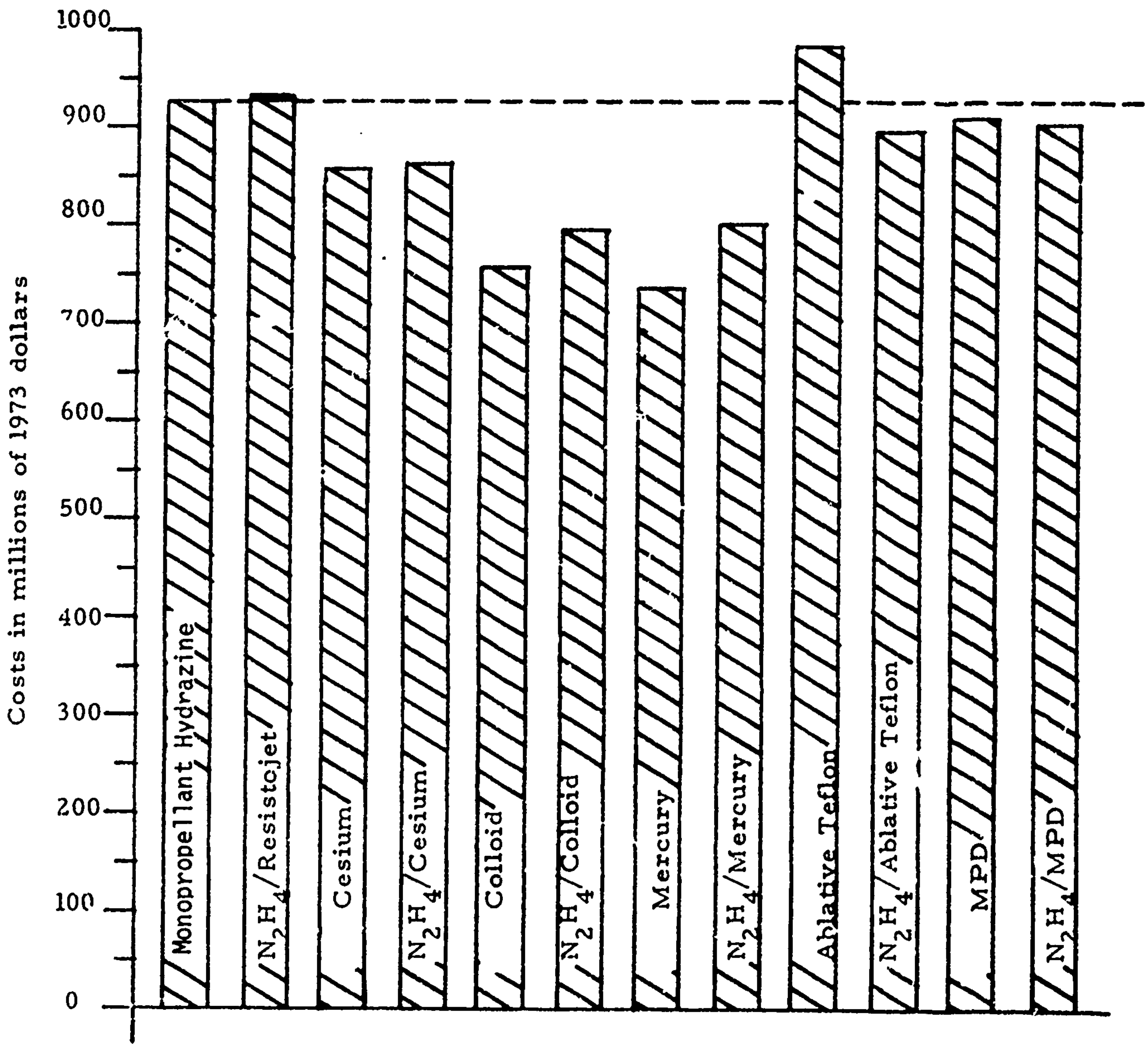

Fig. 20 Ten-Year System Cost of Constellations of Six Medium Category Satellites with Specified Propulsion Subsystems

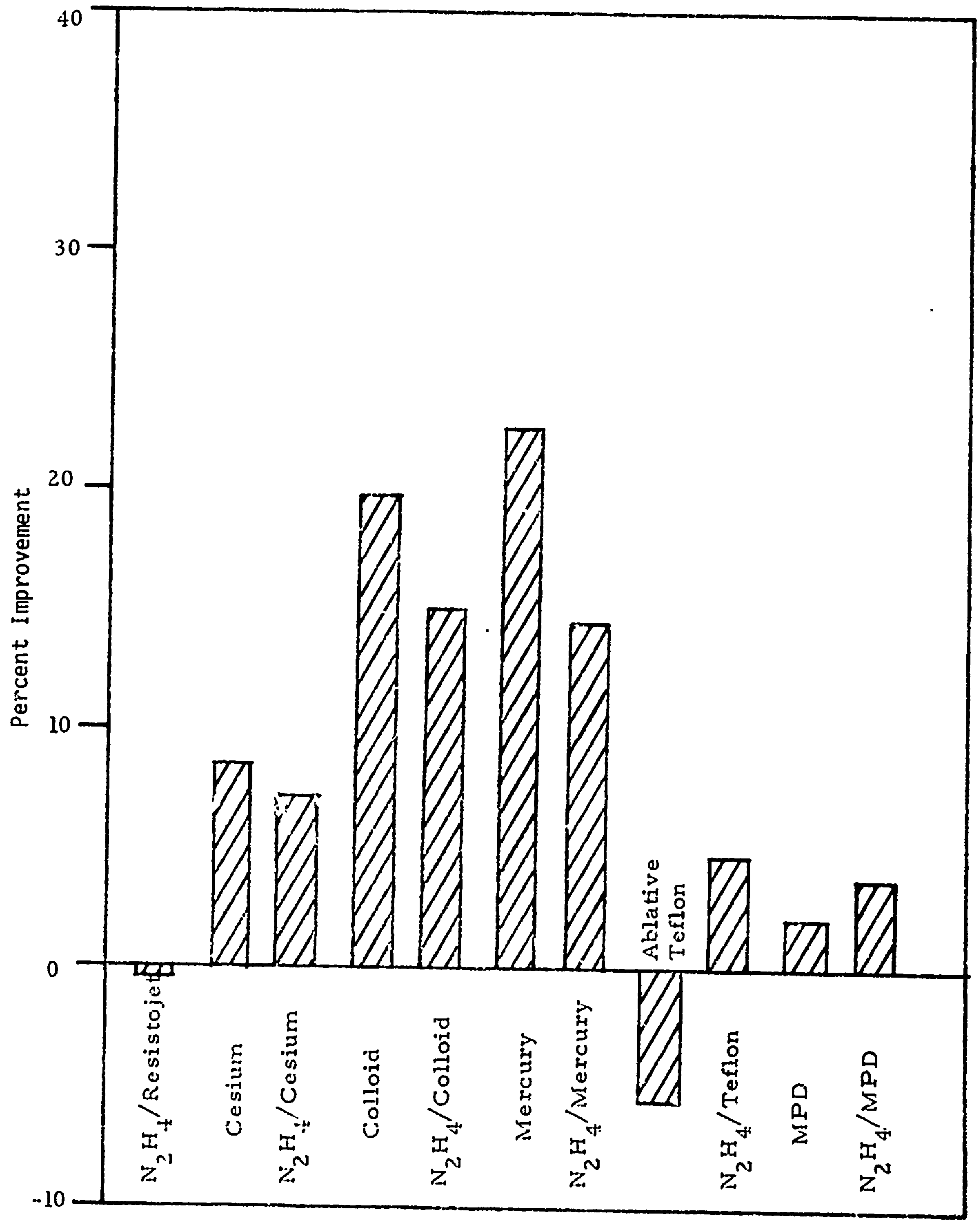

Fig. 21 Percent Reduction in Cost of Constellation of Six Medium Category Satellites with Specified Propulsion Subsystems Compared with Baseline Satellite

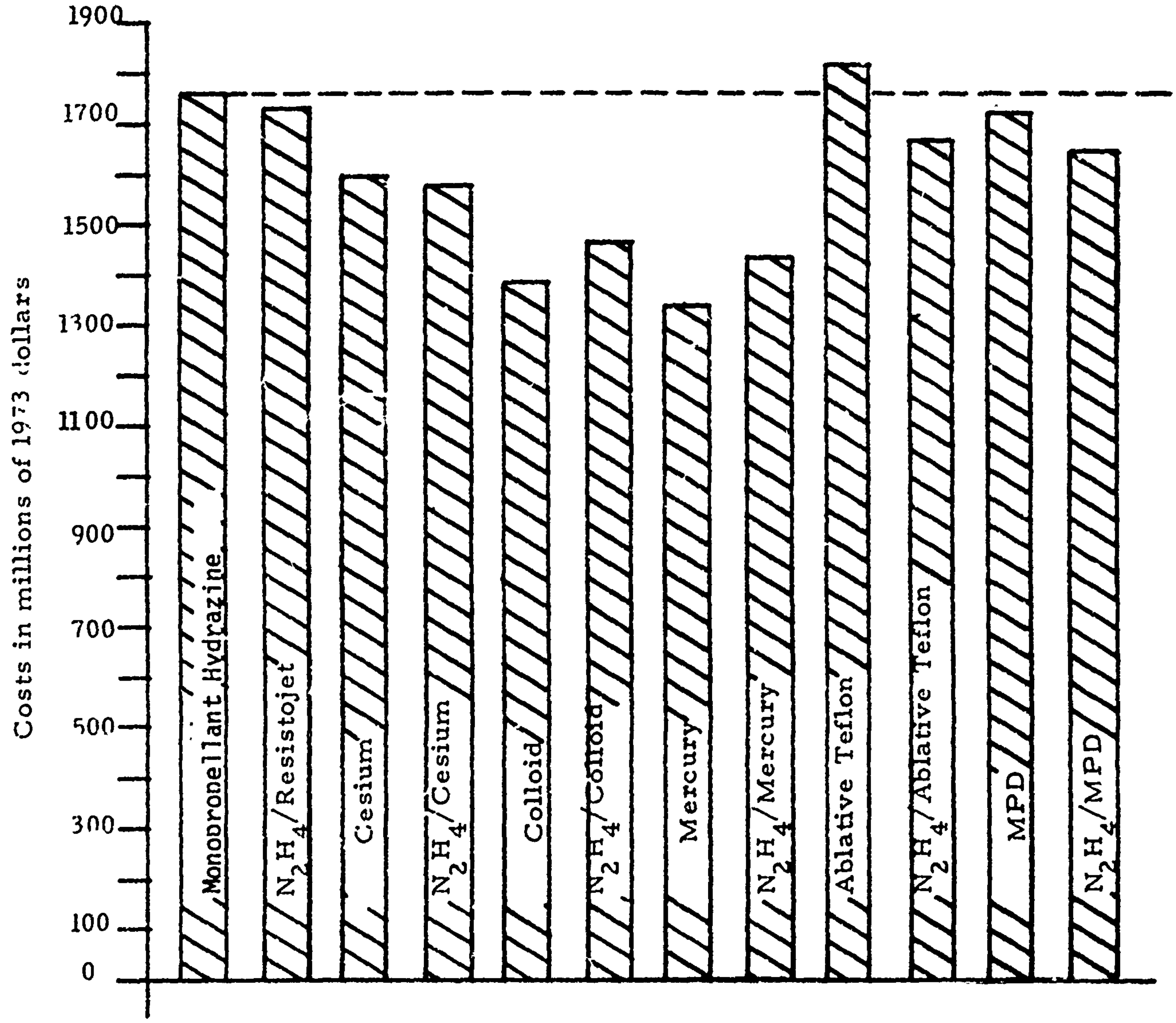

Fig. 22 Ten-Year System Cost of Constellations of Twelve Medium Category Satellites with Specified Propulsion Subsystems.

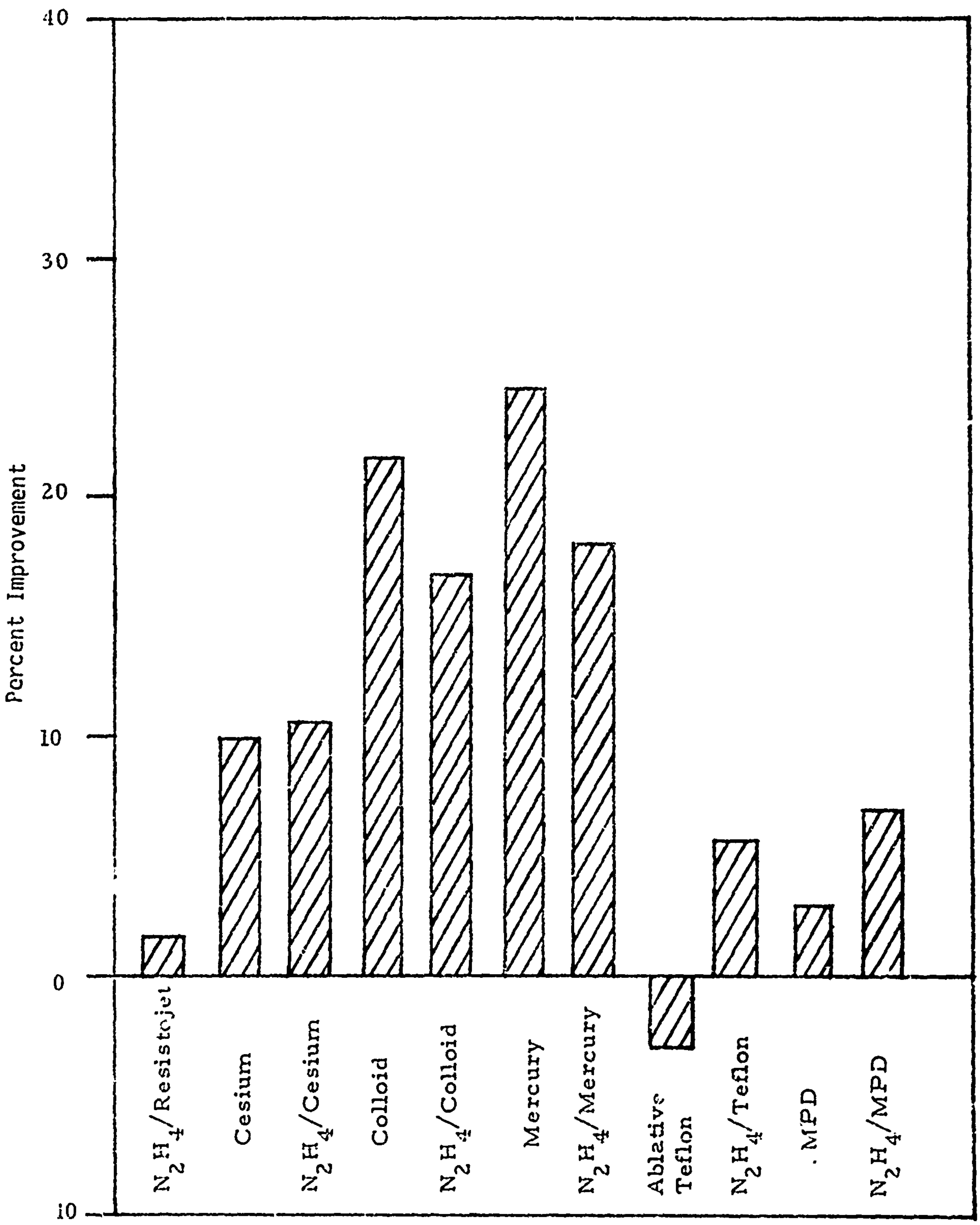

Fig. 23 Percent Reduction in Cost of Constellation of Twelve Medium Category Satellites with Specified Propulsion Subsystems Compared with Baseline Satellite

satellites in orbit. These figures are comparable with the saving of $214 million or 21 percent shown in Table 13, preceding, for a constellation of 12 small category satellites.

e. System Cost Comparisons for Large Category Satellites. Comparisons among the 10-year system costs of the 12 types of large category satellites are presented in Fig. 24 through Fig. 27. Again, the mercury propulsion subsystem without the use of hydrazine thrusters compares favorably, from the standpoint of cost, with all of the other propulsion systems. Satellites with hybrid mercury propulsion rank fourth among the large category satellites in terms of system cost. However, the cost advantage which hybrid colloid shows over hybrid mercury is very small. The difference in the cost of the two types of satellites reflects, in a large measure, the larger power requirements of the hybrid mercury subsystem.

The MPD is the only type of electric propulsion that shows steady improvement in system costs as the weight of the satellite is increased. Small category satellites with MPD propulsion subsystems showed higher 10-year system costs than any of the other satellites under study. In the medium size category, the system costs of satellites with MPD were 2 to 3 percent below the cost of the baseline satellite but were higher than the like costs of all other satellites with electric propulsion except those with ablative teflon subsystems. In the large size category, the 10-year costs of satellites with MPD fell nearly 7 percent below the cost of the baseline and were lower than those of satellites with either all ablative teflon or hybrid ablative teflon.

The cost estimates from which Figs. 24 through 27 were prepared are are given in Tables D5 and D6 in Appendix D. The above cost comparisons were also made from these tables.

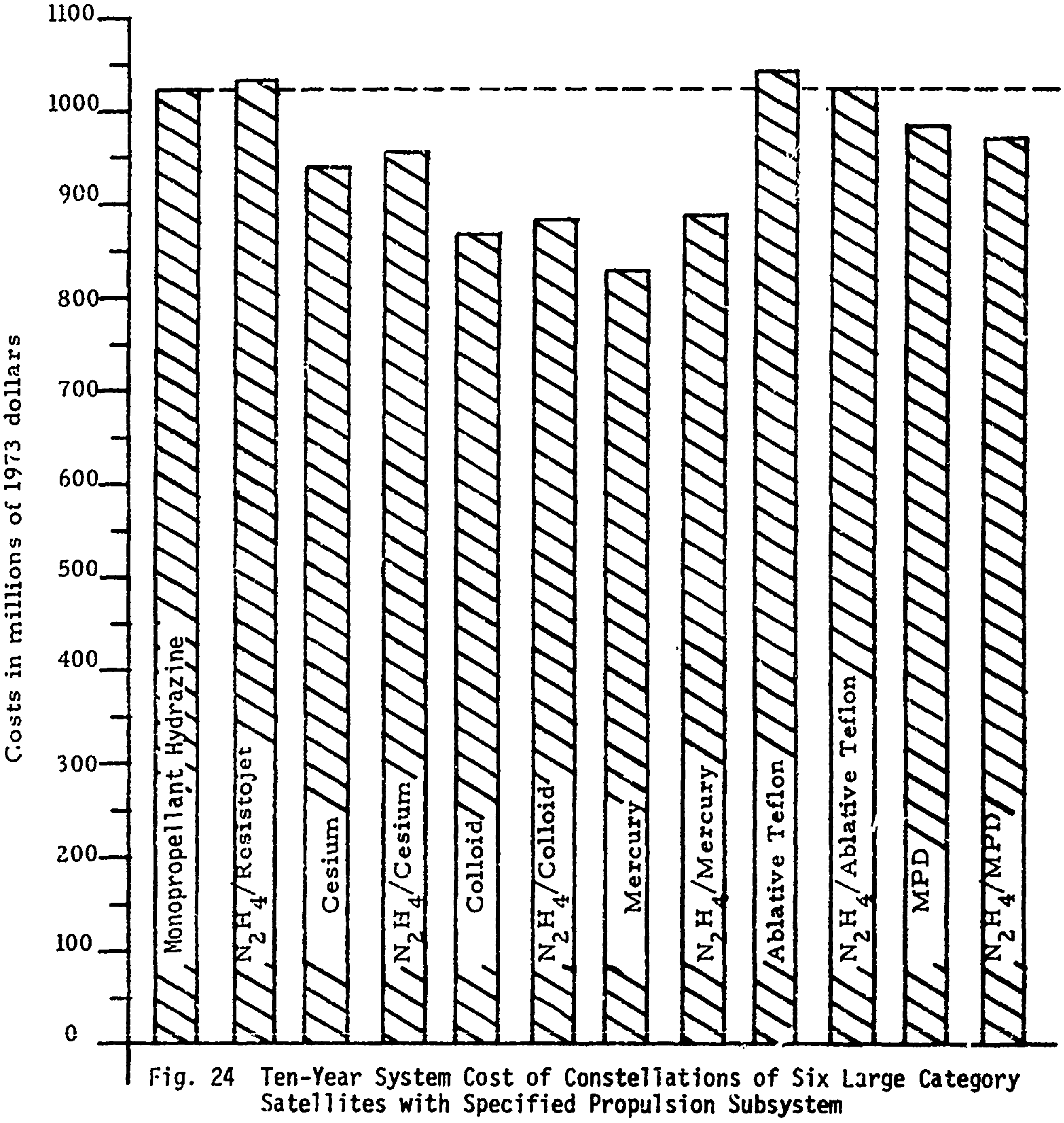

Fig. 24 Ten-Year System Cost of Constellations of Six Large Category Satellites with Specified Propulsion Subsystem

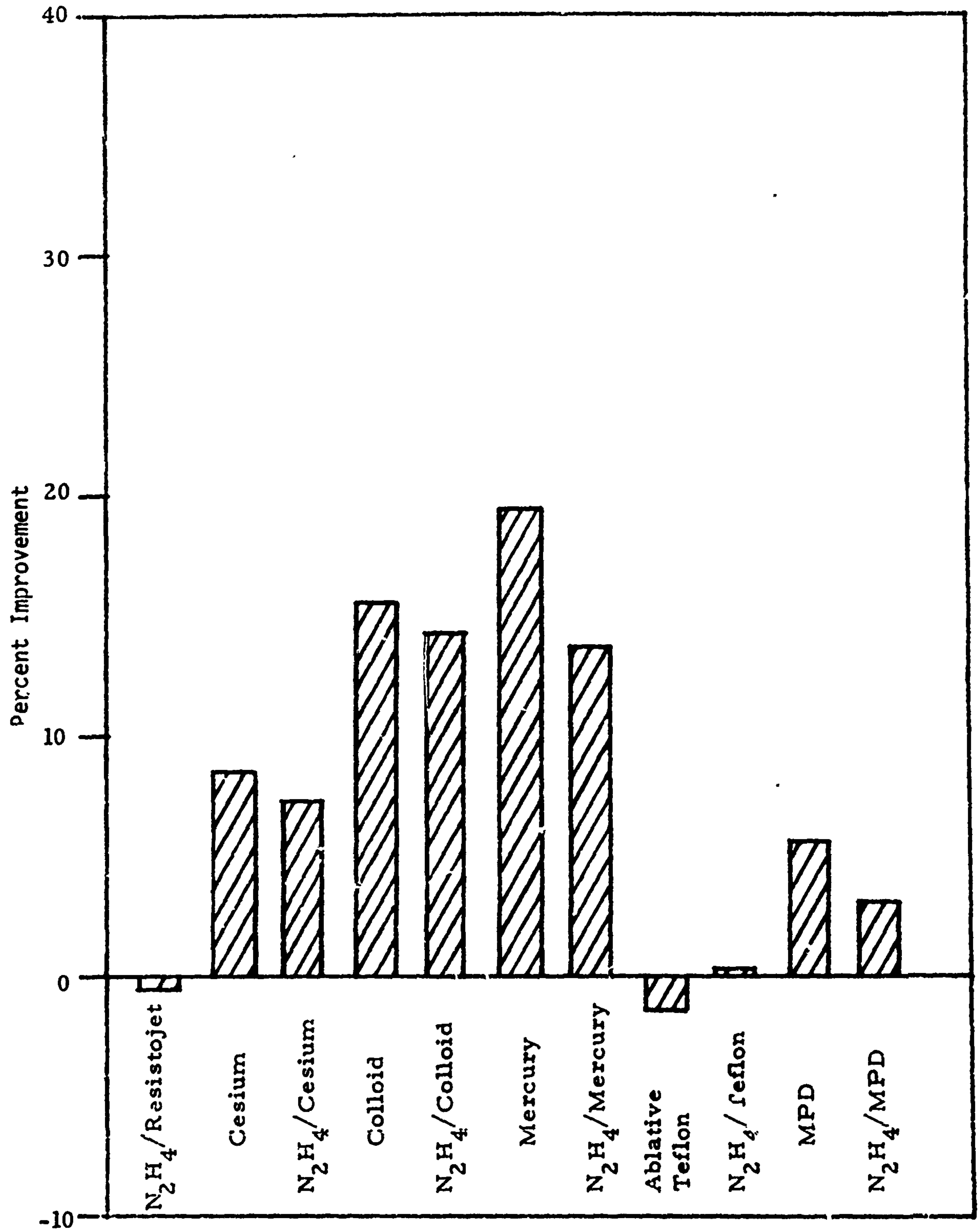

Fig. 25 Percent Reduction in Cost of constellation of Six Large Category Satellites with Specified Propulsion Subsystems Compared with Baseline Satellite

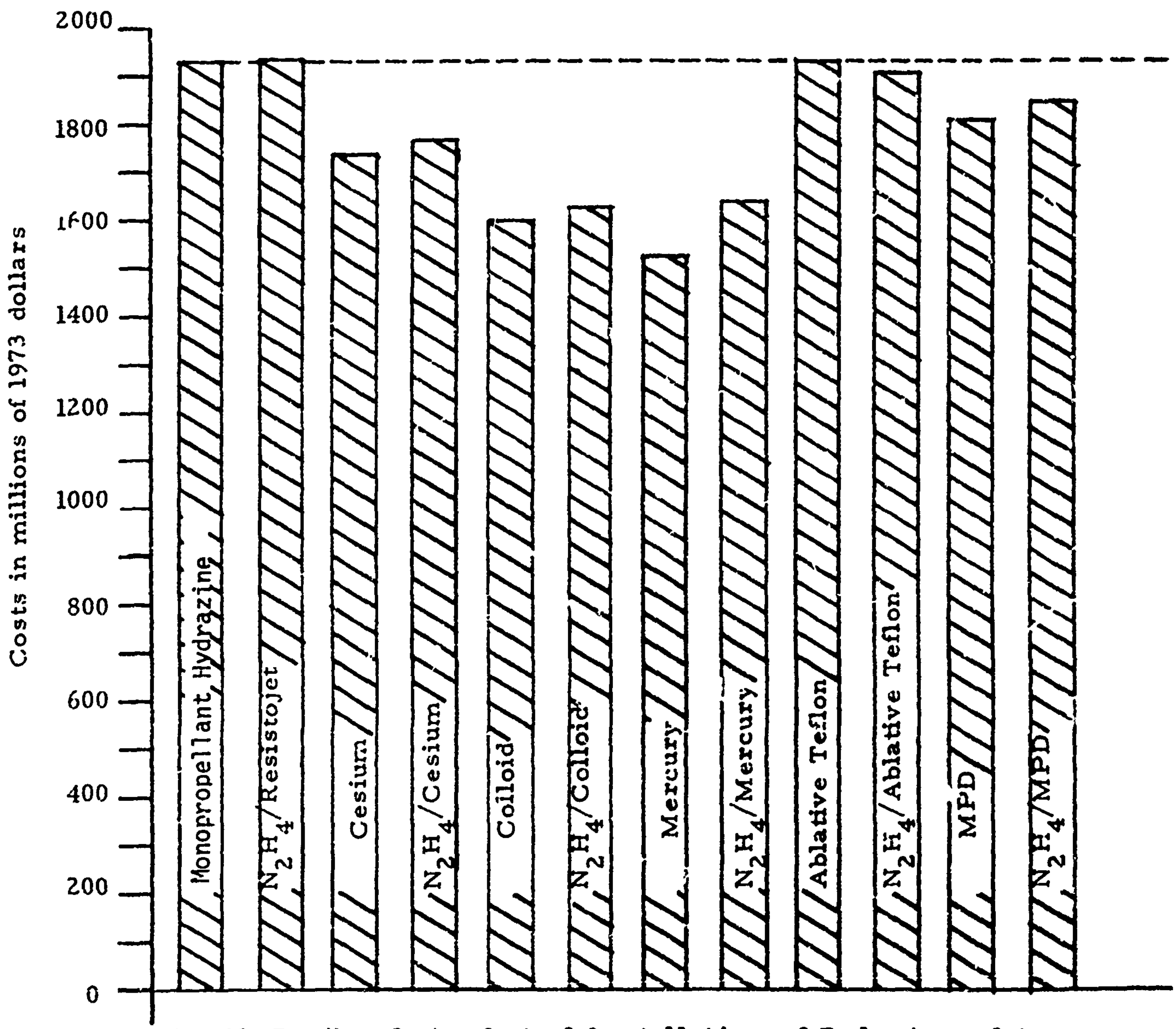

Fig. 26 Ten-Year System Cost of Constellations of Twelve Large Category Satellites with Specified Propulsion Subsystem

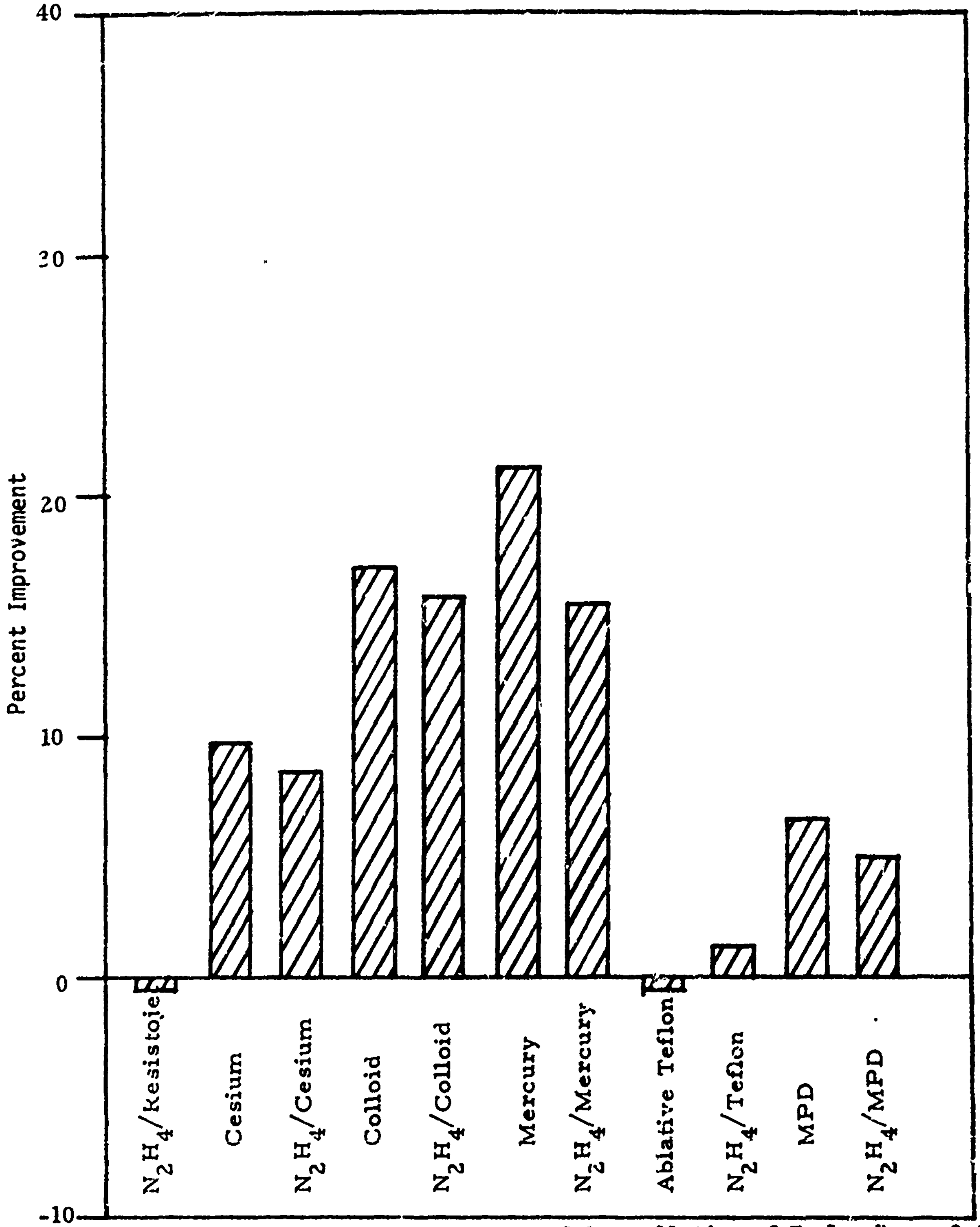

Fig. 27 Percent Reduction in Cost of Constellation of Twelve Large Category Satellites with Specified Propulsion Subsystems Compared with Baseline Satellite

3. INCREASED FLEXIBILITY IN DESIGN AND LAUNCHING OF SATELLITES

a. Basic Concept. The basic concept which underlies this analysis is that if orbit raising by means of electric propulsion is feasible, the design weight of a satellite, or the combined weight of a group of satellites, would be less critical because there would be flexibility with respect to the initial orbit in which the payload is placed. A launch vehicle (possibly a lower cost vehicle) could be chosen that has the capability of placing the payload in an intermediate earth orbit from which it could be spiralled to synchronous equatorial orbit by means of electric propulsion. This increased flexibility also might enable program planners to avoid the cost of developing launch vehicles that otherwise will be required to fill the gap between the capability of the Titan IIIC (3,200 pounds to synchronous equatorial orbit) and that of the Titan IIIC/Centaur which when available will place a 7,200 pound payload in the synchronous orbit.

b. Performance of Selected Launch Vehicles. The major objectives in this part of the analysis are to determine (a) the altitude of the earth circular (intermediate) orbits in which selected launch vehicles would place payloads varying in weight from 1,000 pounds to 20,000 pounds, and (b) the additional characteristic velocity (ΔV_c) that would be required of an electric propulsion system to spiral the payload into synchronous equatorial orbit. The results are shown in Table 14.

First, the characteristic velocity (V_c) to which each of four selected launch vehicles would accelerate payloads of specified weights was determined. The V_c data for the SLV-3D(Atlas)/Centaur/Burner II were taken from Fig. 5-3, Ref. 12. Data for the other three launch vehicles were read from curves in Fig. 3-10 and Fig 4-1, Ref. 13. The altitudes to which each of the characteristic velocities would carry the specified payloads were read from curves

TABLE 14

PERFORMANCE OF SELECTED LAUNCH VEHICLES

Launch Vehicle and Related Information	Gross Weight of Payload (lbs)	Charac-teristic Velocity Vc(Ft/sec)	Altitude (n. mi.) With no Plane Change	With Plane Change
SLV-3A (Atlas)/Agena				
Payload in synch eqn orb 610 lbs net[a]	610	39,600	(b)	19,400
Fairing: diameter: 5A	1,000	38,400	10,800	7,300
Fairing Weight: 812 lbs	2,000	35,400	6,700	
Type of Shroud:	3,000	33,000	3.700	
Adapter Weight:	4,000	31,000	2,200	
Cost:[c] Non-Recurring Cost $1.6M	5,000	29,600	1,600	
Unit Recurring Cost $11.6M				
SLV-3D(Atlas)/Centaur/Burner II				
Payload in synch eqn orb 1900 lbs net[a]	1,900	39,600	(b)	19,400
Fairing: Diameter: 10 ft	2,000	39,400	(b)	10,000
Fairing Weight: 2940 lbs	3,000	36,000	7,800	
Type of Shroud: "Surveyor"	4,000	33,800	4,450	
Adapter Weight: 20 lbs. (50#)	5,000	32,300	3,100	
Cost:[c] Non-Recurring Cost NONE	6,000	30,800	2,170	
Unit Recurring Cost $15.2M	8,000	28,500	1,100	
Titan IIIC				
Payload in Synch eqn orb 3,220 lbs.	3,220	39,600	(b)	19,400
Fairing: diameter: 10 ft; length 25 ft.	4,000	38,600	(b)	18,300
Type of Shroud: "Titan (UPLF)"	5,000	37,750	13,500	3,700
Jettison Weight: 1967 lbs	6,000	36,700	9,800	
Adapter Weight: 230 lbs	8,000	35,200	6,400	
Cost:[c] Non-Recurring Cost NONE	10,000	33,700	4,700	
Unit Recurring Cost $19.5M.	20,000	29,000	1,300	
Titan IIIE/Centaur				
Payload in synch eqn orb 7200 lbs	7,200	39,600	(b)	19,400
Fairing: diameter: 14 ft; length 55 ft	8,000	39,400	(b)	15,400
Type of Shroud: "Viking"	10,000	37,500	12,500	3,100
Jettison Weight: 6060 lbs	20,000	31,200	2,370	
Adapter Weight: 116 lbs				
Cost:[c] Non-Recurring Cost NONE				
Unit Recurring Cost $25.2M				

a. Approximate net weight of payload if the apogee kick motor is in the satellite.
b. The velocity not required to lift the specified payload to synchronous altitude would be utilized to make part of the plane change.
c. All costs are in terms of 1973 dollars.

(continued)

TABLE 14 (continued)

Launch Vehicle and Related Information	Additional Velocity (ΔV_c) Required(ft/se) To 24-hr Synch. Alt.	To Synch Equatorial Orbit	Time to Spiral to Synch Equa. Orbit (thrust/weight = 10^{-5} using Elec. Prop.) (in days)
SLV-3A(Atlas)/Agena			
Payload in synch eqn orb 610 lbs. net[a]	None	None	---
	2,677	6,045	2,173
	4,986		
	7,923		
	10,130		
	11,360		
SLV-3D(Atlas)/Centaur/Burner II			
Payload in synch eqn orb 1900 lbs net[a]	None	None	---
	1,500	2,775	997
	4,305		
	7,109		
	8,843		
	10,158		
	12,375		
Titan IIIC			
Payload in Synch eqn orb 3,220 lbs.	None	None	---
	None	1,270	456
	1,637		
	3,174		
	5,215		
	8,095		
	12,045		
Titan IIIE/Centaur			
Payload in synch eqn orb 7200 lbs.	None	None	---
	None	1,000	359
	1,687		
	9,981		

a. Approximate net weight of payload if the apogee kick motor is in the satellite.

in Fig. 3-1, Ref. 12. The altitudes attainable both with or without plane change are shown in Table 14.

The additional velocity (ΔV_C) required either to raise the satellite to 24-hour synchronous altitude without plane change or to place the satellite in synchronous equatorial orbit (with plane change) is listed in the table. The ΔV_C needed for a Hohmann transfer was calculated from Equation 7 and these values are plotted in Fig. 7. Each value was corrected by adding the low thrust penalty shown in the figure. The corrected values are entered in the next to the last column of Table 14. The time required to spiral the satellite to synchronous equatorial orbit using low thrust (thrust/weight $= 10^{-5}$) electrical propulsion is shown in the last column of the table

Estimates of the costs associated with each of the launch vehicles and the weight and size of the fairings and shrouds are included in the table for convenient reference. Determination of the cost of the launch vehicles is explained in connection with Table 11.

c. Orbit Raising. The purpose of this section of the report is to consider the feasibility of selecting smaller and less expensive launch vehicles to place satellites or groups of satellites into some intermediate orbit and utilize the on-board propulsion system to insert the vehicle into synchronous equatorial orbit. Table 14 lists the candidate launch vehicles and the ΔV_C increments required with and without plane change. The plane changes are required to place the satellite into synchronous equatorial orbit.

Using tangential thrust, constant acceleration, and Isp's consistent with the cesium ion engine employed in the first part of the analysis (Ref. 14), Fig. 28 was generated. The data indicates that any millipound thrust device to take a satellite to synchronous orbit demands transit times in excess of

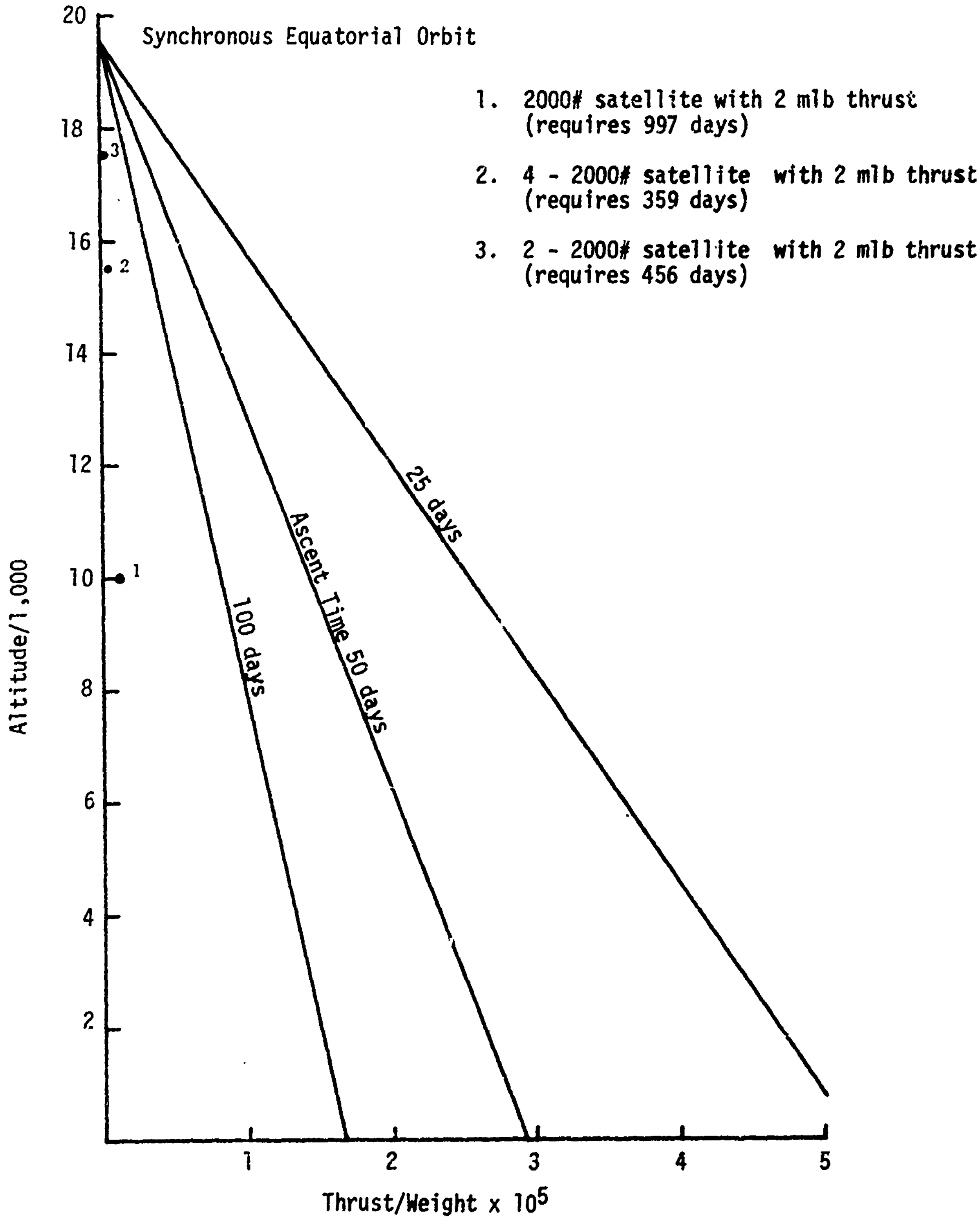

Fig. 28 Minimum Thrust Requirements for Spiraling to Orbit

those considered practicable. For example, using the Titan IIIC, as shown in Table 14, a transit time of 456 days would be required to spiral a 4,000 pound satellite from an intermediate circular orbit of 18,300 nautical miles to synchronous equatorial orbit. Other launch vehicles considered in Table 14 which might be used to place the satellite in an intermediate orbit would require even longer transit times. Factoring larger values of thrust still produces times-to-orbit that are excessive. Furthermore, after a level of 4 millipounds of thrust is reached, the weight savings become nonexistent in the missions analyzed and consequently no projected increase in life is possible.

An investigation was also conducted to see if there were any combinations of launch vehicles and satellites where advantages could accrue from spiralling into synchronous orbit. For this case, the intermediate orbit would have to be relatively high (above 15,000 NM). No specific areas were identified; consequently the utilization of the electric propulsion for orbit raising in this mission was not considered further.

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APPENDIX A

DETERMINATION OF SATELLITE SUBSYSTEM WEIGHTS

The purpose of this appendix is to present the data and methodology used in determining the weights of three major subsystems of the satellites under study, namely, (a) structure, including thermal control and [illegible]stage, (b) telemetry, tracking and command (TT & C), and (c) communications, which is the mission package. Weights of the other two major subsystems of the satellites, as explained in Section VII, were either generated by the Rocket Propulsion Laboratory computer program or obtained from contractors or from studies of propulsion subsystems. The weights estimated in this appendix are for satellites with a 3-year mean missions duration (MMD). The weights assigned to satellites with 4-year, 5-year and 7-year MMDs were computed by applying weight growth factors to the weights determined for the 3-year satellites. The weight growth factors were computed from data in an Aerospace Corporation report (Ref. 7).

The procedure followed in estimating the subsystem weights for satellites with a 3-year MMD was first to determine preferred weights for each of the three major subsystems. These preferred weights served as initial inputs in the weight analysis. By means of a reiterative procedure, these initial weights, along with those generated by the computer, were adjusted slightly to conform with the constraints placed upon the various subsystems. The adjustments in the preferred weights were generally downward, but in each instance, the adjusted weight was large enough to be consistent with experience data taken from existing satellite programs.

Detailed weight data were obtained from twelve satellite programs of the Air Force and the National Aeronautics and Space Administration. The

satellites in eight of the programs are 3-axis stabilized; whereas those in the other four programs are spin stabilized. For the Program 777 satellites data were available for both operational and programmed satellites. Both sets of data were utilized. As a result, thirteen data points appear on each of the three accompanying graphs.

The weights of the five major subsystems in each type of satellite were expressed as percentages of the total weight of the satellite. The percentages obtained for each of the three subsystems under study were then plotted as a function of the total weight of the satellite (Fig. A1 through Fig. A3). In each of these figures, the data points for the 3-axis stabilized satellites are represented by a 3-pronged indicator "γ". The corresponding percentages for the spin stabilized satellites are represented by an "x". In determining a preferred value for each of the three major subsystems, the data points for 3-axis satellites were given added weight compared with the data for spin stabilized satellites. This was advisable since the satellites under study are 3-axis stabilized. The percentages, or range in percentages, which the adjusted subsystem weights (discussed in the second paragraph above) comprise of the total weight of the satellite are indicated by short vertical lines located above the 1000, 2000, and 3000 pound gradients on the abscissa of each graph.

Fig. A1 presents the above described data points for the structure subsystems of the satellites. It will be observed that although there is considerable variation among types of satellites with respect to the proportion of total weight that is devoted to structure, these percentage variations appear to be largely independent of the total weight of the satellite. The adjusted weights of the structure subsystems used in the present study

comprise 21.1 percent of the total weight of the small category satellites with a 3-year MMD. The corresponding percentages for medium and large category satellites are 22.0 and 21.6, respectively. These percentages are represented by small vertical dashes in the graph.

The proportion of total satellite weight that is devoted to the mission package, which in the satellites under consideration is communications, is shown in Fig. A2. In this instance, there is a distinct tendency for the percentage of total weight that is available for the mission package to increase as the weight of the satellite increases. The adjusted weights of the communications subsystems of the satellites for which estimates were made comprise from 21.9 percent to 25.2 percent of the total weight of the small category satellites. Comparable percentages for the medium category satellites range from 28.3 to 32.4. The large category satellites show even larger proportions devoted to the communications subsystems, namely, from 32.5 percent to 36.5 percent. The range in percentages of weight devoted to communications in each of the three categories of satellites is depicted by vertical lines in Fig. A2. These vertical lines indicate that the adjusted weights determined for the communications subsystems of satellites with a 3-year MMD are consistent with the experienced data used in preparing the graph.

The data points plotted in Fig. A3 show the extent to which the proportion of satellite total weight devoted to the telemetry, tracking and command (TT & C) subsystem decreases as the weight of the satellite increases. The percentages of total weight computed from the adjusted weights of the TT & C subsystems range from 7.0 to 8.1 for small category satellites and from 6.0 to 6.9 for medium category satellites. Corresponding percentages for large category satellites are 4.4 and 4.9. These percentages, represented by

short vertical lines in Fig. A3, indicate that the adjusted subsystem weights of satellites with a 3-year MML are consistent with data compiled from existing satellite programs.

The weight growth factors that were applied to the subsystem weights for 3-year satellites to determine the corresponding weights for satellites with longer mean mission durations are listed in Table 7, Section VII. The procedure followed in applying the factors and the results obtained are illustrated in the table.

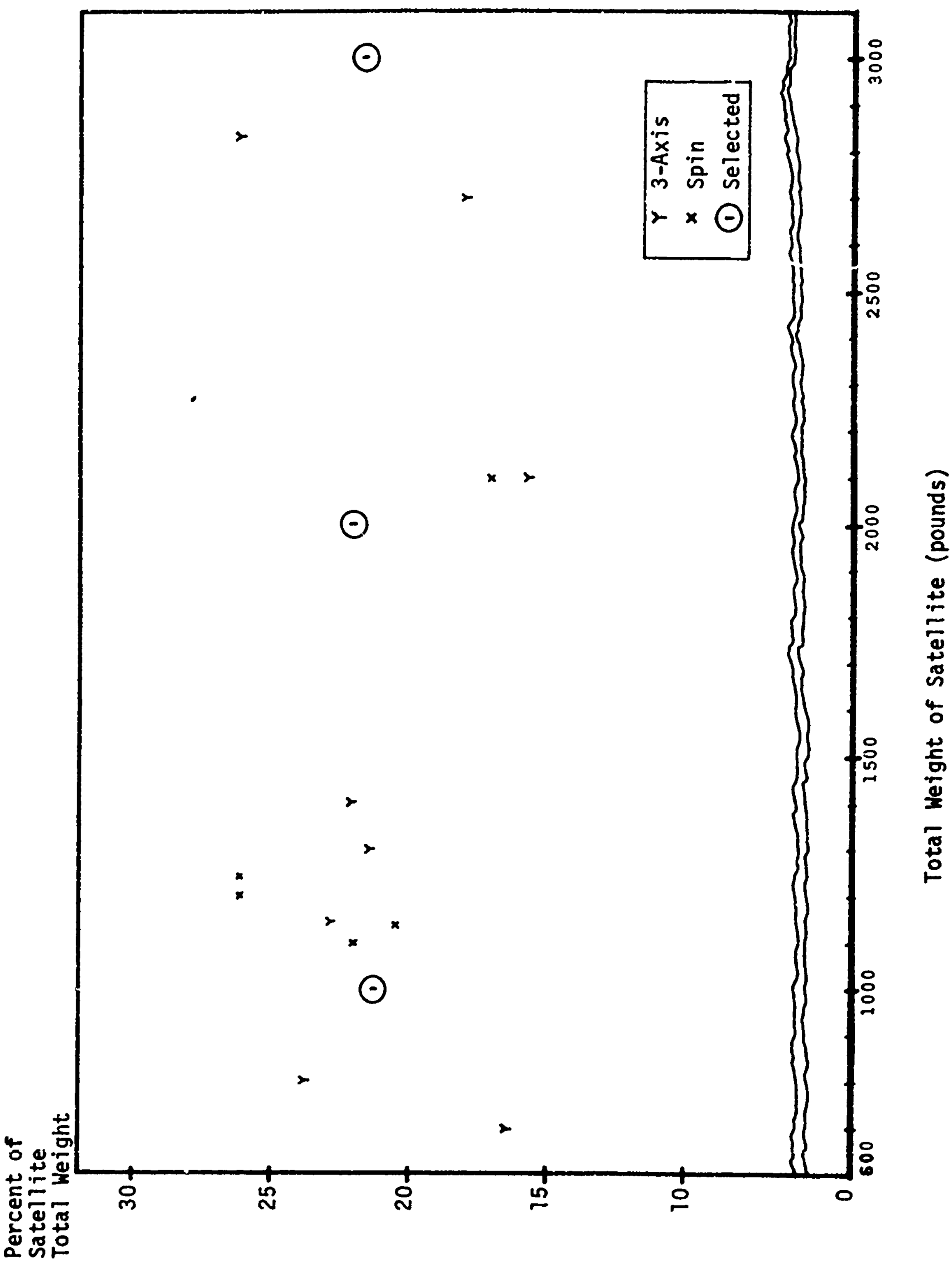


Fig. A1 Structure Subsystem Weight as a Percentage of Satellite Total Weight

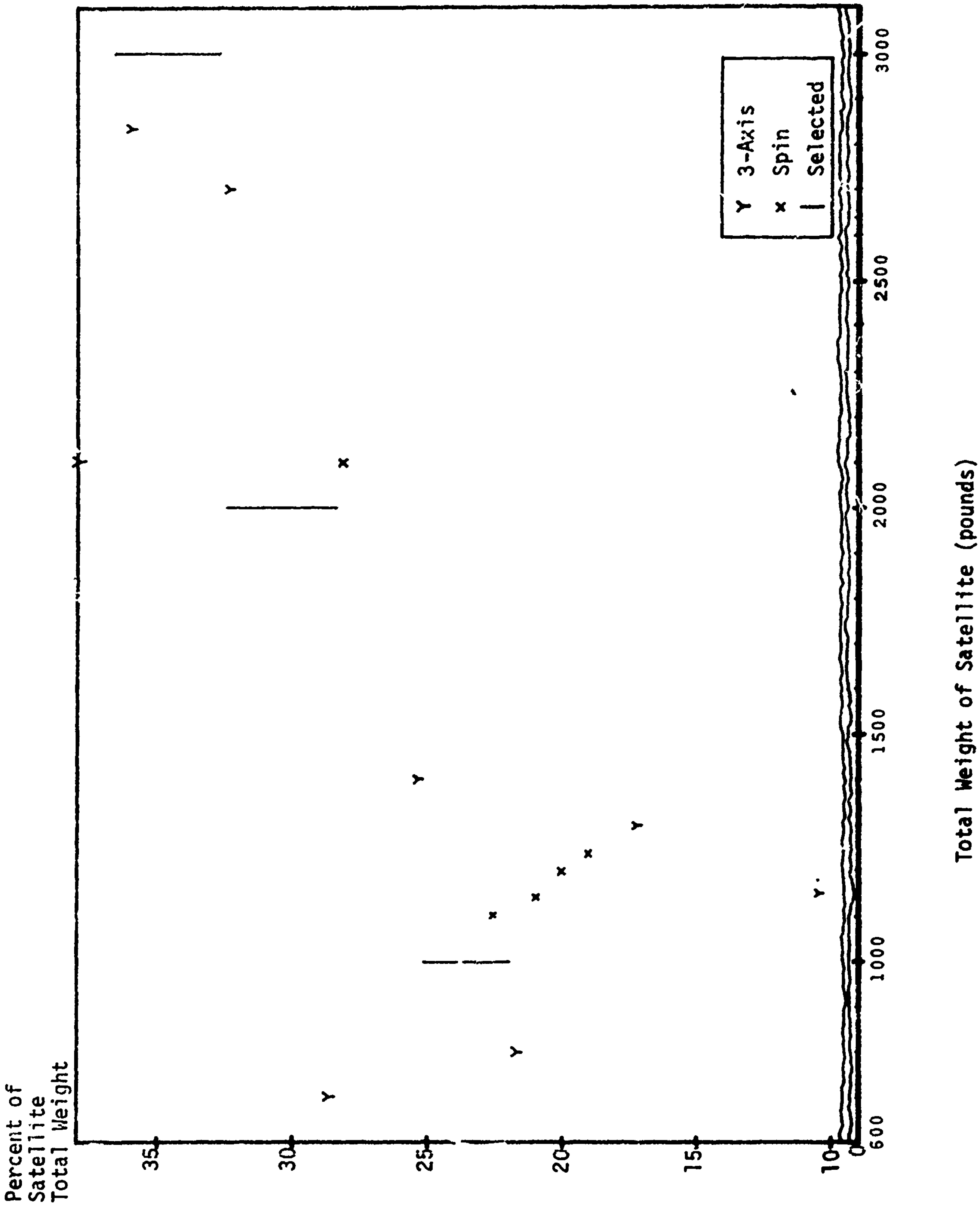


Fig. A2 Communications Subsystem Weight as a Percentage of Satellite Total Weight

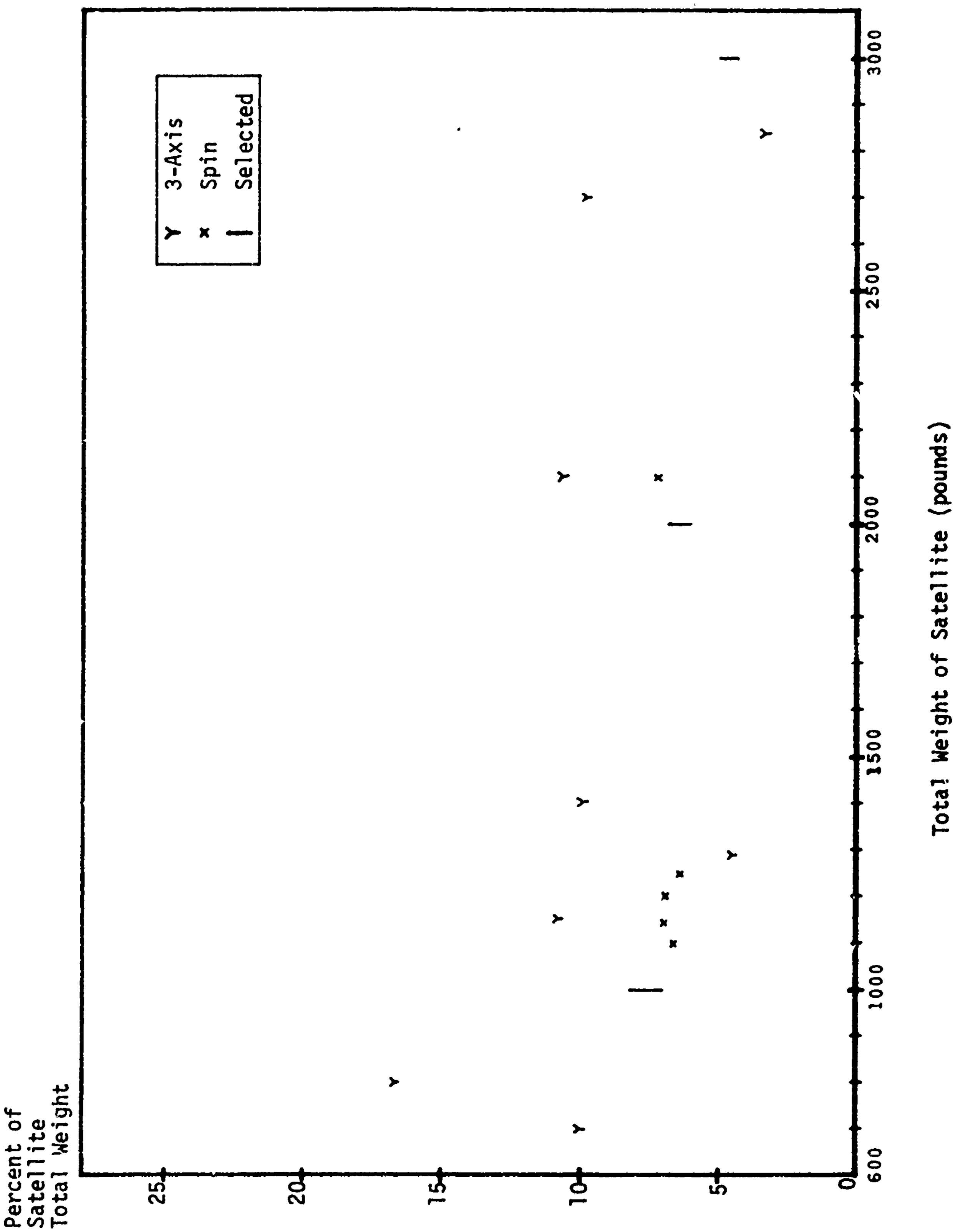


Fig. A3 Telemetry, Tracking and Command Subsystem Weight as a Percentage of Satellite Total Weight

APPENDIX B

TABLES 1 THROUGH 3

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION

TABLE B1

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Small Category Satellites
(Weight in pounds)

Satellite Subsystem	Monopropellant Hydrazine N_2H_4 3 Year	4 Year	5 Year	7 Year	N_2H_4/Resistojet 3 Year	4 Year	5 Year	7 Year
Structure	211.5	225.7	235.3	247.4	203.9	217.6	227.3	238.5
TT and C	70.0	70.3	76.0	84.2	70.0	70.3	76.0	84.2
Communications	219.0	262.1	291.9	335.5	219.0	262.1	291.9	335.5
Electric Power:								
Elec. Distribution	69.0	69.8	70.7	76.9	67.0	67.7	68.7	74.6
Power Control	31.0	31.0	31.8	35.9	30.1	30.1	30.9	34.9
Batteries	88.5	88.5	90.7	118.1	86.0	86.0	88.2	114.7
Solar Panels	42.6	42.9	43.1	43.9	41.4	41.6	41.9	42.7
Attitude Control	268.4	330.5	401.0	553.8	249.5	309.1	379.6	521.9
Total Satellite Weight	1000.0	1120.8	1241.0	1495.7	966.9	1084.5	1204.5	1447.0

(continued)

TABLE B1 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Small Category Satellites
(Weight in pounds)

Satellite Subsystem	Cesium (Cs) 3 Year	Cesium (Cs) 4 Year	Cesium (Cs) 5 Year	Cesium (Cs) 7 Year	N_2H_4/Cesium (Cs) 3 Year	N_2H_4/Cesium (Cs) 4 Year	N_2H_4/Cesium (Cs) 5 Year	N_2H_4/Cesium (Cs) 7 Year
Structure	203.0	216.6	226.3	237.4	193.9	206.9	216.2	226.8
TT and C	70.0	70.3	76.0	84.2	70.0	70.3	76.0	84.2
Communications	219.0	262.1	291.9	335.5	219.0	262.1	291.9	335.5
Electric Power:								
Elec. Distribution	89.7	90.7	91.9	100.0	78.4	79.3	81.3	87.4
Power Control	40.3	40.3	41.3	46.7	35.2	35.2	36.1	40.8
Batteries	115.1	115.1	118.0	153.5	100.6	100.6	103.1	134.2
Solar Panels	55.4	55.7	56.0	57.1	48.4	48.7	49.0	49.9
Attitude Control	167.1	184.5	214.7	259.4	172.0	192.7	223.3	270.0
Total Satellite Weight	959.6	1035.3	1116.1	1273.8	917.5	995.8	1076.9	1228.8

(continued)

TABLE B1 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Small Category Satellites
(Weight in pounds)

Satellite Subsystem	Colloid 3 Year	Colloid 4 Year	Colloid 5 Year	Colloid 7 Year	N_2H_4/Colloid 3 Year	N_2H_4/Colloid 4 Year	N_2H_4/Colloid 5 Year	N_2H_4/Colloid 7 Year
Structure	183.3	195.6	204.4	214.4	184.9	197.3	206.2	216.2
TT and C	70.0	70.3	76.0	84.2	70.0	70.3	76.0	84.2
Communications	219.0	262.1	291.9	335.5	219.0	262.1	291.9	335.5
Electric Power:								
Elec. Distribution	71.1	71.9	72.9	79.2	69.1	69.9	71.6	77.0
Power Control	31.9	31.9	32.7	37.0	31.1	31.1	31.9	36.0
Batteries	91.2	91.2	93.5	121.7	88.6	88.6	90.8	118.2
Solar Panels	43.9	44.1	44.4	45.2	42.7	42.9	43.2	44.0
Attitude Control	157.2	180.6	211.5	266.3	169.6	194.6	228.6	284.6
Total Satellite Weight	867.6	947.7	1027.3	1183.5	875.0	956.8	1040.2	1195.7

(continued)

TABLE B1 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Small Category Satellites
(Weight in pounds)

	Mercury (Hg)				N_2H_4/Mercury (Hg)			
Satellite Subsystem	3 Year	4 Year	5 Year	7 Year	3 Year	4 Year	5 Year	7 Year
Structure	186.4	198.9	207.8	218.0	184.9	197.3	206.2	216.2
TT and C	70.0	70.3	76.0	84.2	70.0	70.3	76.0	84.2
Communications	219.0	262.1	291.9	335.5	219.0	262.1	291.9	335.5
Electric Power:								
Elec. Distribution	80.5	81.4	82.5	89.7	73.8	74.6	75.6	82.2
Power Control	36.2	36.2	37.1	42.0	33.2	33.2	34.0	38.5
Batteries	103.3	103.3	105.9	137.8	94.7	94.7	97.1	126.3
Solar Panels	49.7	50.0	50.3	51.2	45.6	45.9	46.1	47.0
Attitude Control	136.0	153.8	179.9	220.1	153.8	175.4	204.4	249.6
Total Satellite Weight	881.1	956.0	1031.4	1178.5	875.0	953.5	1031.3	1179.5

(continued)

TABLE B1 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Small Category Satellites
(Weight in pounds)

Satellite Subsystem	Ablative Teflon				N_2H_4/Ablative Teflon			
	3 Year	4 Year	5 Year	7 Year	3 Year	4 Year	5 Year	7 Year
Structure	206.9	220.8	230.7	242.0	197.0	210.2	219.7	230.4
TT and C	70.0	70.3	76.0	84.2	70.0	70.3	76.0	84.2
Communications	219.0	262.1	291.9	335.5	219.0	262.1	291.9	335.5
Electric Power:								
Elec. Distribution	85.8	86.7	87.9	95.5	76.5	77.3	78.4	85.2
Power Control	38.5	38.5	39.5	44.6	34.4	34.4	35.3	39.9
Batteries	110.0	110.0	112.8	146.7	98.1	98.1	100.6	130.9
Solar Panels	61.8	62.1	62.5	63.7	51.6	51.9	52.2	53.2
Attitude Control	186.2	207.6	243.2	300.0	184.9	209.6	244.6	301.7
Total Satellite Weight	978.2	1058.1	1144.5	1312.2	931.5	1013.9	1098.7	1261.0

(continued)

TABLE B1 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Small Category Satellites

(Weight in pounds)

	MPD				N_2H_4/MPD			
Satellite Subsystem	3 Year	4 Year	5 Year	7 Year	3 Year	4 Year	5 Year	7 Year
Structure	212.8	227.1	237.3	248.9	198.5	211.8	221.3	232.1
TT and C	70.0	70.3	76.0	84.2	70.0	70.3	76.0	84.2
Communications	219.0	262.1	291.9	335.5	219.0	262.1	291.9	335.5
Electric Power:								
Elec. Distribution	87.4	88.4	89.6	97.4	77.3	78.2	79.2	86.2
Power Control	39.3	39.3	40.3	45.5	34.7	34.7	35.6	40.2
Batteries	112.1	112.1	114.9	149.5	99.1	99.1	101.6	132.2
Solar Panels	54.0	54.3	54.6	55.6	47.7	48.0	48.3	49.2
Attitude Control	211.3	230.6	269.8	328.1	192.5	214.4	249.6	303.7
Total Satellite Weight	1005.9	1084.2	1174.4	1344.7	938.8	1018.6	1103.5	1263.3

TABLE B2

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Medium Category Satellites
(Weight in pounds)

	Monopropellant Hydrazine N_2H_4				N_2H_4/Resistojet			
Satellite Subsystem	3 Year	4 Year	5 Year	7 Year	3 Year	4 Year	5 Year	7 Year
Structure	440.0	469.5	490.6	514.6	436.4	465.6	486.6	510.3
TT and C	120.0	120.5	130.2	144.4	120.0	120.5	130.2	144.4
Communications	565.0	676.3	753.1	864.4	565.0	676.3	753.1	864.4
Electric Power:								
Elec. Distriubtion	124.1	125.5	127.2	138.3	125.9	127.3	129.0	140.3
Power Control	55.8	55.8	57.2	64.7	56.6	56.6	58.0	65.6
Batteries	159.2	159.2	163.2	212.4	161.6	161.6	165.6	215.6
Solar Panels	76.7	77.1	77.6	79.0	77.8	78.3	78.8	80.2
Attitude Control	459.2	580.8	720.4	1010.4	439.5	557.7	695.6	981.3
Total Satellite Weight	2000.0	2264.7	2519.5	3028.2	1982.8	2243.9	2496.9	3002.1

(continued)

TABLE B2 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Medium Category Satellites
(Weight in pounds)

	Cesium (Cs)				N_2H_4/Cesium (Cs)			
Satellite Subsystem	3 Year	4 Year	5 Year	7 Year	3 Year	4 Year	5 Year	7 Year
Structure	417.3	445.3	465.3	488.0	412.6	440.2	460.0	482.5
TT and C	120.0	120.5	130.2	144.4	120.0	120.5	130.2	144.4
Communications	565.0	676.3	753.1	864.4	565.0	676.3	753.1	864.4
Electric Power:								
Elec. Distribution	159.9	161.7	163.9	178.2	148.6	150.2	152.3	165.6
Power Control	71.8	71.8	73.6	83.2	66.8	66.8	68.5	75.5
Batteries	205.0	205.0	210.1	273.5	190.6	190.6	195.4	260.6
Solar Panels	98.7	99.3	99.9	101.7	91.7	92.3	92.8	94.5
Attitude Control	259.1	288.3	336.6	409.7	279.7	315.8	368.8	454.5
Total Satellite Weight	1896.8	2068.2	2232.7	2543.1	1875.0	2052.7	2221.1	2542.0

(continued)

TABLE B2 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Medium Category Satellites
(Weight in pounds)

	Colloid				N_2H_4/Colloid			
Satellite Subsystem	3 Year	4 Year	5 Year	7 Year	3 Year	4 Year	5 Year	7 Year
Structure	391.0	417.2	436.0	457.2	395.9	422.4	441.4	463.0
TT and C	120.0	120.5	130.2	144.4	120.0	120.5	130.2	144.4
Communications	565.0	676.3	753.1	864.4	565.0	676.3	753.1	864.4
Electric Power:								
Elec. Distribution	131.9	133.4	135.2	147.0	130.0	131.4	133.3	144.8
Power Control	59.3	59.3	60.8	68.7	58.4	58.4	59.9	67.7
Batteries	169.2	169.2	173.4	196.1	166.7	166.7	170.9	222.4
Solar Panels	81.4	81.9	82.4	83.9	80.2	80.7	81.2	82.7
Attitude Control	258.9	299.9	356.0	450.4	282.1	328.5	394.2	501.0
Total Satellite Weight	1776.7	1957.7	2127.1	2412.1	1798.3	1984.9	2164.2	2490.4

(continued)

TABLE B2 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Medium Category Satellites
(Weight in pounds)

Satellite Subsystem	Mercury (Hg) 3 Year	4 Year	5 Year	7 Year	N_2H_4/Mercury (Hg) 3 Year	4 Year	5 Year	7 Year
Structure	383.6	409.3	427.7	448.6	395.3	421.8	440.8	462.3
TT and C	120.0	120.5	130.2	144.4	120.0	120.5	130.2	144.4
Communications	565.0	676.3	[illegible]3.1	864.4	565.0	673.6	753.1	864.4
Electric Power:								
Elec. Distribution	135.7	137.2	139.1	151.2	139.4	140.9	142.9	155.2
Power Control	61.0	61.0	62.5	70.7	62.6	62.6	64.2	74.4
Batteries	174.1	174.1	178.4	232.2	178.8	178.8	183.2	238.5
Solar Panels	90.2	90.7	91.3	92.9	86.1	86.6	87.1	88.7
Attitude Control	214.1	244.7	287.6	355.6	249.3	286.9	337.6	421.7
Total Satellite Weight	1743.7	1913.8	2069.9	2360.0	1796.5	1971.7	2139.1	2449.6

(continued)

TABLE B2 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Medium Category Satellites
(Weight in pounds)

Satellite Subsystem	Ablative Teflon				N_2H_4/Ablative Teflon			
	3 Year	4 Year	5 Year	7 Year	3 Year	4 Year	5 Year	7 Year
Structure	443.7	473.4	494.7	518.8	431.3	460.2	480.9	504.4
TT and C	120.0	120.5	130.2	144.4	120.0	120.5	130.2	144.4
Communications	565.0	673.6	753.1	864.4	565.0	673.6	753.1	864.4
Electric Power:								
Elec. Distribution	175.4	177.3	179.8	195.4	158.9	160.7	162.9	177.1
Power Control	78.8	78.8	80.8	91.2	71.4	71.4	73.2	82.8
Batteries	224.9	224.9	230.5	300.0	203.8	203.8	208.9	271.9
Solar Panels	108.3	108.9	109.6	111.6	98.1	98.8	99.3	101.1
Attitude Control	301.2	340.1	401.2	504.6	312.1	356.6	420.5	529.0
Total Satellite Weight	2017.3	2197.5	2379.9	2730.4	1960.6	2145.6	2329.0	2675.1

(continued)

TABLE B2 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Medium Category Satellites
(Weight in pounds)

Satellite Subsystem	MPD 3 Year	MPD 4 Year	MPD 5 Year	MPD 7 Year	N_2H_4/MPD 3 Year	N_2H_4/MPD 4 Year	N_2H_4/MPD 5 Year	N_2H_4/MPD 7 Year
Structure	432.3	461.3	482.0	505.5	421.4	449.6	469.9	492.8
TT and C	120.0	120.5	130.2	144.4	120.0	120.5	130.2	144.4
Communications	565.0	673.6	753.1	864.4	565.0	673.6	753.1	864.4
Electric Power:								
Elec. Distribution	156.4	158.1	160.3	174.2	146.3	147.9	151.6	163.0
Power Control	70.3	70.3	72.0	81.5	65.7	65.7	67.3	76.2
Batteries	200.6	200.6	205.6	267.6	187.6	187.6	192.3	250.3
Solar Panels	96.6	97.1	97.7	99.5	90.3	90.9	91.4	93.1
Attitude Control	323.2	355.3	416.3	511.0	319.1	357.5	420.0	520.0
Total Satellite Weight	1964.4	2136.8	2317.2	2648.1	1915.4	2093.3	2275.6	2604.2

TABLE B3 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Large Category Satellites

(Weight in pounds)

	Monopropellant Hydrazine N_2H_4				N_2H_4/Resistojet			
Satellite Subsystem	3 Year	4 Year	5 Year	7 Year	3 Year	4 Year	5 Year	7 Year
Structure	648.9	692.4	723.5	759.5	646.3	689.6	720.6	755.8
TT and C	131.7	132.2	142.9	158.4	131.7	132.2	142.9	158.4
Communications	975.7	1167.9	1300.6	1494.9	975.7	1167.9	1300.6	1494.9
Electric Power:								
Elec. Distribution	175.8	177.7	180.2	195.8	180.3	182.3	184.8	200.9
Power Control	79.0	79.0	81.0	91.6	81.0	81.0	83.0	93.9
Batteries	225.6	225.6	231.2	298.7	231.3	231.3	237.1	306.2
Solar Panels	109.1	109.7	110.4	112.4	111.3	112.0	112.7	114.7
Attitude Control	654.2	837.1	1044.2	1479.8	631.2	810.3	1015.0	1446.3
Total Satellite Weight	3000.0	3421.6	3814.0	4591.1	2988.8	3406.6	3796.7	4571.1

(continued)

TABLE B3 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Large Category Satellites

(Weight in pounds)

Satellite Subsystem	Cesium (Cs) 3 Year	4 Year	5 Year	7 Year	N_2H_4/Cesium (Cs) 3 Year	4 Year	5 Year	7 Year
Structure	610.4	651.3	680.6	713.8	611.3	652.3	681.6	714.9
TT and C	131.7	132.2	142.9	158.4	131.7	132.2	142.9	158.4
Communications	975.7	1167.9	1300.6	1494.9	975.7	1167.9	1300.6	1494.9
Electric Power:								
Elec. Distribution	225.4	227.9	231.0	251.1	214.1	216.5	219.5	238.5
Power Control	101.3	101.3	103.8	117.4	96.2	96.2	98.6	111.5
Batteries	289.1	289.1	296.3	382.8	274.6	274.6	281.5	363.6
Solar Panels	139.2	140.0	140.8	143.4	132.2	133.0	133.8	136.2
Attitude Control	349.1	390.0	455.9	557.3	390.8	443.4	519.2	643.0
Total Satellite Weight	2821.9	3099.7	3351.9	3819.1	2826.6	3116.1	3377.7	3861.0

(continued)

TABLE B3 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Large Category Satellites
(Weight in pounds)

Satellite Subsystem	Colloid				N_2H_4/Colloid			
	3 Year	4 Year	5 Year	7 Year	3 Year	4 Year	5 Year	7 Year
Structure	579.0	617.8	645.6	677.1	586.5	625.8	653.9	685.9
TT and C	131.7	132.2	142.9	158.4	131.7	132.2	142.9	158.4
Communications	975.7	1167.9	1300.6	1494.9	975.7	1167.9	1300.6	1494.9
Electric Power:								
Elec. Distribution	188.4	190.5	193.1	209.9	186.2	188.2	190.9	207.4
Power Control	84.5	84.5	86.6	97.9	83.6	83.6	85.7	96.9
Batteries	241.3	241.3	247.3	319.5	238.8	238.8	244.8	316.2
Solar Panels	116.2	116.9	117.6	119.7	115.0	115.6	116.3	118.5
Attitude Control	359.1	418.7	498.7	637.7	394.5	461.8	549.9	702.5
Total Satellite Weight	2675.9	2969.8	3232.4	3715.1	2712.0	3013.9	3285.0	3780.7

(continued)

TABLE B3 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Large Category Satellites
(Weight in pounds)

Satellite Subsystem	Mercury (Hg) 3 Year	Mercury (Hg) 4 Year	Mercury (Hg) 5 Year	Mercury (Hg) 7 Year	N_2H_4/Mercury (Hg) 3 Year	N_2H_4/Mercury (Hg) 4 Year	N_2H_4/Mercury (Hg) 5 Year	N_2H_4/Mercury (Hg) 7 Year
Structure	579.3	618.1	645.9	677.5	586.5	625.8	653.9	685.9
TT and C	131.7	132.2	142.9	158.4	131.7	132.2	142.9	158.4
Communications	975.7	1167.9	1300.6	1494.9	975.7	1167.9	1300.6	1494.9
Electric Power:								
Elec. Distribution	207.0	209.3	212.2	230.6	200.3	202.5	205.3	223.2
Power Control	93.0	93.0	95.3	107.8	90.0	90.0	92.3	104.3
Batteries	265.5	265.5	272.1	351.5	256.9	256.9	263.3	340.1
Solar Panels	127.8	128.6	129.3	131.7	123.7	124.4	125.2	127.5
Attitude Control	298.4	342.3	403.8	501.7	347.0	402.2	474.9	596.8
Total Satellite Weight	2678.4	2957.4	3202.1	3654.1	2711.8	3001.9	3258.4	3731.1

(continued)

TABLE B3 (continued)

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Large Category Satellites
(Weight in pounds)

Satellite Subsystem	Ablative Teflon 3 Year	Ablative Teflon 4 Year	Ablative Teflon 5 Year	Ablative Teflon 7 Year	N_2H_4/Ablative Teflon 3 Year	N_2H_4/Ablative Teflon 4 Year	N_2H_4/Ablative Teflon 5 Year	N_2H_4/Ablative Teflon 7 Year
Structure	646.1	689.4	720.4	755.6	638.0	680.7	711.4	746.1
TT and C	131.7	132.2	142.9	158.4	131.7	132.2	142.9	158.4
Communications	975.7	1167.9	1300.6	1494.9	975.7	1167.9	1300.6	1494.9
Electric Power:								
Elec. Distribution	246.1	248.8	252.3	274.2	229.7	232.2	235.4	255.9
Power Control	110.6	110.6	113.4	128.2	103.2	103.2	105.8	119.6
Batteries	315.7	315.7	323.6	418.0	294.6	294.6	302.0	390.1
Solar Panels	152.0	152.9	153.8	156.6	141.8	142.6	143.5	146.1
Attitude Control	409.4	464.7	548.7	687.5	435.2	501.1	593.0	751.2
Total Satellite Weight	2987.3	3282.2	3555.7	4073.4	2949.9	3254.5	3534.6	4062.3

TABLE B3

SATELLITE WEIGHT AS A FUNCTION OF TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION (MMD)

Large Category Satellites
(Weight in pounds)

Satellite Subsystem	MPD 3 Year	MPD 4 Year	MPD 5 Year	MPD 7 Year	N_2H_4/MPD 3 Year	N_2H_4/MPD 4 Year	N_2H_4/MPD 5 Year	N_2H_4/MPD 7 Year
Structure	629.2	671.6	701.8	736.1	623.6	665.4	695.3	729.3
TT and C	131.7	132.2	142.9	158.4	131.7	132.2	142.9	158.4
Communications	975.7	1167.9	1300.6	1494.9	975.7	1167.9	1300.6	1494.9
Electric Power:								
Elec. Distribution	220.8	223.2	226.3	246.0	210.7	213.0	216.0	234.7
Power Control	99.2	99.2	101.7	115.0	94.7	94.7	97.1	109.8
Batteries	283.2	283.2	290.3	375.0	270.2	270.2	277.0	357.7
Solar Panels	136.3	137.1	138.0	140.5	130.1	130.9	131.6	134.0
Attitude Control	433.3	478.5	562.4	691.4	446.7	502.9	592.6	737.0
Total Satellite Weight	2909.4	3192.9	3464.0	3957.3	2883.4	3177.2	3453.1	3955.8

(continued)

APPENDIX C

SATELLITE COST MODEL

The purpose of this appendix is to make available the cost estimating relationships (CERs) and related cost factors that were used in estimating (a) all nonrecurring costs associated with the development and testing of each type and size of satellite under study, and (b) the first unit cost of each of the satellites. The CERs and cost factors were incorporated into a computerized cost model, but they could be used manually. The complete computer program which generated the basic cost estimates cited above is reproduced herein for possible use by interested readers.

The cost estimating equations that were used in computing the satellite subsystem direct costs are listed in Table C1. The CERs for four subsystems, namely, structure, TT & C, communications, and electric power source, were adopted from the Unmanned Spacecraft Cost Model developed by the Cost Analysis Division, Hq SAMSO. The only modifications made in the CERs were (a) the insertion of a factor in each equation which allows for cost escalation from 1970 to 1973 and (b) the derivation of two equations to estimate costs of communications subsystems that are heavier than those on which the SAMSO cost relationships are based. The cost escalation factors, namely, 1.1675 for nonrecurring costs and 1.1606 for recurring costs, were computed from another SAMSO report (Ref. 8).

The two CERs that were developed for the heavier communications subsystems are listed in Table C1 as items B (1) and (2) under "Communications Subsystem". These equations constitute an extrapolation of the SAMSO CER based on information obtained from Headquarters National Aeronautics and Space Administration (NASA) and the Jet Propulsion Laboratory. The NASA

costs, although higher than those of the Air Force, revealed trends that are similar to those depicted by the SAMSO curve within the weight limits for which data are available from the two sources. It was therefore postulated that the slope of the NASA curve is indicative of the trend in Air Force costs, and the two CERs were developed to provide straight line approximations of the slope of the NASA curve.

The CERs for the attitude control subsystem of a 3-axis stabilized satellite are updated equations received by phone from the Cost Analysis Division, Hq SAMSO. These equations were used in estimating subsystem costs of the satellites that use monopropellant hydrazine, namely, the baseline satellite and the one that employs the N_2H_4/Resistojet propulsion subsystem.

Since the SAMSO CERs for the propulsion elements of the attitude control subsystem are based on satellites using chemical propulsion, it was necessary to develop CERs that would indicate more accurately the cost of attitude control systems of satellites that employ electric propulsion. Based upon information obtained from the Jet Propulsion Laboratory, equations were developed to provide estimates of both recurring and nonrecurring costs of ion thrusters, power conditioning units, propellant tanks, and propellants for electric propulsion subsystems. The costs of control sensors and mechanisms in the attitude control systems were estimated by modifying the SAMSO equations to use the weight of the sensors and mechanisms in lieu of the dry weight of the entire subsystem. The above mentioned CERs for electric propulsion subsystems are shown under the last five major headings in Table C1.

The CERs presented in Table C1, and discussed above, provide estimates of the cost that are directly and exclusively related to the specified subsystems. Satellite costs other than those directly related to a particular subsystem include (a) cost of the dispenser, aerospace ground equipment (AGE) and launch

operations, (b) program level costs, (c) burden and general expense, and (d) contractor fee.

The costs of dispensers used in the present analysis were taken from the Program 777 satellites, namely, \$58,000 in nonrecurring costs and \$25,000 in recurring costs. The cost of AGE for satellites employing electric propulsion subsystems and having a 3-year MMD is estimated at \$4.89 million, based on an estimate supplied by the Cost Analysis Division, Hq SAMSO, for medium size new development programs. The AGE cost for the baseline satellite is an average computed from the cost of the AGE for a follow-on system and that of a medium-size new program. The cost of AGE for the 3-year satellite using monopropellant hydrazine is thus estimated at \$3.665 million. The cost of the AGE for satellites with longer mean mission duration were calculated by multiplying the AGE cost for the appropriate 3-year satellite by 1.050 for a 4-year satellite, 1,083 for a 5-year satellite, and 1.133 for a satellite with a 7-year MMD.

Program level costs, launch operations costs, burden and general expenses, and fee were factored in using the percentages listed in Table C2. The percentage factors for program level costs and for burden and general expense in recurring costs were taken from the SAMSO report (Ref. 10). The percentage factors for fee and for burden and general expense in nonrecurring costs are slightly lower than those used by SAMSO.

All of the above mentioned CERs and cost factors are incorporated in the computer program which is reproduced in Table C3. Provision is made in this program for inputing "inheritance" factors which would differentiate among the various types of satellites with respect to the technology and development that would be transferable from other programs. However, the limited amount of information that was available concerning the comparative

state of development of the several electric propulsion subsystems did not warrant establishment of inheritance factors to be used in the cost computations.

The computer program generates and summarizes the nonrecurring costs incident to the development and testing of the specified type of satellite. It also provides the first unit (production) cost of the satellite, but it does not compute total satellite system costs. As explained in Section VIII and illustrated in Tables 12 and 13, Section IX, it is necessary to determine the number of satellites required for a specified program and then to calculate the cumulative average unit cost of the required number of satellites by applying appropriate learning curve factors to the first unit cost generated by the computer program. To the total satellite cost must be added the cost of launch vehicles used to place the satellite in the desired orbit. The launch operations costs included in the satellite costs constitute only the cost of preparing and servicing the satellite at the time of launch.

TABLE C1

COST ESTIMATING RELATIONSHIPS (CERs) FOR UNMANNED SPACECRAFT

Structure, Thermal Control, and Interstage Subsystem

A. Nonrecurring Cost CER

$$NRSTC_{1973\ \$10^3} = 1.1675\ [632.56 + 23.08(Wt:\ lbs)^{0.66}]$$

B. Unit Recurring Cost CER

$$URSTC_{1973\ \$10^3} = 1.1606\ [54.19 + 0.93(Wt:\ lbs)^{0.94}]$$

Communications Subsystem (Mission Package or Payload)

A. Nonrecurring Cost CER

$$NRPLC_{1973\ \$10^3} = 1.1675\ [332.0(Wt:\ lbs)^{0.44}]$$

B. Unit Recurring Cost CER

(1) If subsystem weight is 230 pounds or less

$$URPLC_{1973\ \$10^3} = 1.1606\ [7.77 + 4.83(Wt:\ lbs)]$$

(2) If subsystem weight is more than 230 pounds but not greater than 600 pounds

$$URPLC_{1973\ \$10^3} = 970 + 1.43(Wt:\ lbs)$$

(3) If subsystem weight is more than 600 pounds

$$URPLC_{1973\ \$10^3} = 1570 + 0.425(Wt:\ lbs)$$

Telemetry, Tracking, and Command Subsystem

A. Nonrecurring Cost CER

$$NRTTC_{1973\ \$10^3} = 1.1675\ [824.47 + 13.78(Wt:\ lbs)]$$

B. Unit Recurring Cost CER

$$URTTC_{1973\ \$10^3} = 1.1606\ [-85.05 + 7.98(Wt:\ lbs)]$$

TABLE C1 (continued)

Electric Power Supply Subsystem

A. Nonrecurring Cost CER

$$NRPWC_{1973\ \$10^3} = 1.1675\ [120.84(\text{Max Array Output: watts})^{0.45}]$$

B. Unit Recurring Cost CER

$$URPWC_{1973\ \$10^3} = 1.1606\ [8.96(\text{Max Array Output: watts})^{0.63}]$$

Attitude Control Subsystem (3-Axis Stabilized) for Chemical Subsystems Only

A. Nonrecurring Cost CER

$$NRACS_{1973\ \$10^3} = 1.1675\ [1285.37 + 16.13(\text{Dry Wt: lbs})]$$

B. Unit Recurring Cost CER

$$URACS_{1973\ \$10^3} = 1.1606\ [62.78 + 7.35(\text{Dry Wt: lbs})] +$$
$$.001[\text{Propellant Cost/lb}_{1973\ \$}(\text{Prop. Wt: lbs})]$$

Ion Thrusters in Electric Propulsion Subsystems

A. Nonrecurring Cost CER

$$NRT_{1973\ \$10^3} = 1.1675\ [1250 + 0.75(\text{BOL Pwr: watts})]$$

B. Unit Recurring Cost CER

$$URT_{1973\ \$10^3} = 1.1606\ [28 + 0.031(\text{BOL Pwr: watts})]$$

Power Conditioning in Electric Propulsion Subsystems

A. Nonrecurring Cost CER

$$NRPC_{1973\ \$10^3} = 1.1675\ [1480 + 0.51(\text{BOL Pwr: watts})]$$

B. Unit Recurring Cost CER

$$URPC_{1973\ \$10^3} = 1.1606\ [70 + 0.06(\text{BOL Pwr: watts})]$$

TABLE C1 (continued

Controls (sensors & mechanisms) in Electric Propulsion Subsystems)

A. Nonrecurring Cost CER

$$NRASUB_{1973\ \$10^3} = 1.1675\ [1285.37 + 18.13(Wt:\ lbs)]$$

B. Unit Recurring Cost CER

$$URASUB_{1973\ \$10^3} = 1.1606\ [62.78 + 7.35(Wt:\ lbs)]$$

Propellant Tanks in Electric Propulsion Subsystems

A. Nonrecurring Cost CER

$$NRPT_{1973\ \$10^3} = 1.1675\ [210 + 30(Wt:\ lbs)]$$

B. Unit Recurring Cost CER

$$URPT_{1973\ \$10^3} = 1.1606\ [0.63 + 1.14(Wt:\ lbs)]$$

Propellants for Electric Propulsion Subsystems

A. Nonrecurring Cost CER

$$NRP_{1973\ \$10^3} = 0.001\ [\text{Propellant cost per lb}_{1973\ \$}(Wt:\ lbs)]$$

B. Unit Recurring Cost CER

$$URP_{1973\ \$10^3} = 0.001\ [\text{Propellant cost per lb}_{1973\ \$}(Wt:\ lbs)]$$

TABLE C2

FACTORS USED IN COMPUTING SATELLITE COSTS OTHER THAN SUBSYSTEM DIRECT COSTS

COST ELEMENT	PERCENTAGE FACTOR Nonrecurring Cost	PERCENTAGE FACTOR Unit Recurring Cost	BASE TO WHICH PERCENTAGE IS APPLIED
Program Level	50%	30%	Cost of subsystems, dispenser & AGE
Launch Operations	--	3%	Above listed costs plus program level
Burden and G&A	82%	106%	Total direct cost
Contractor Fee	10%	10%	Total direct cost plus B and G/A

TABLE C3

COMPUTER PROGRAM FOR CALCULATING SATELLITE COSTS

```
      PROGRAM COSTSAT(INPUT,OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT)
      TYPE REAL NRSTC,NRTTC,NRPLC,NRPWC,NRACSC,NRPL,NRDC,NRBGA,NRTSC,
      INRTOTS, NRASUB
      DIMENSION XAMSAT(3)
C     THIS PROGRAM CALCULATES COSTS BASED ON SAMSO AND OAS CERS
      DATA (DISPN=58.), (AGEBLX=3665.),(AGENSX=4890.),(DISPU=25.0),
     1(PCNH=3.00)
    1 FORMAT(3A6,I2,5X,5F10.1)
  110 FORMAT(///,28X,*STRUCTURE*,4X,*TTC*,4X,*PAYLOAD* 2X,*ELECT PWR *,3
     1X,*ACS*,7X,*ACSSM*,2X,*THRUSTER*,2X,*POWER COND*,3X,*TANKS*,6X,*PR
     1OP.*
   10 FORMAT(///,28X,*STRUCTURE*,4X,*TTC*,4X,*PAYLOAD*2X,*ELECT PWR *,4
     1X,*ACS*
   16 FORMAT(3A6,I2,5X,4F10.1,6F10.1)
    2 FORMAT( 8X,*NONRECURRING COST*,5F10.1)
    3 FORMAT( 7X;*UNITRECURRING COST*,5F10.1)
    4 FORMAT(/,2X,*NRPL=*F10.1,2X,*NRDC=*,F10.1,2X,*NRBGA=*,F10.1,2X,*FE
     1E=*,F10.1,2X,*NRTSC=*,F10.1)
    5 FORMAT(5X*URPL=*F10.1,2X,*URLU=*,F10.1,2X,*URDC=*,F10.1,2X,*URBG
     1GA=*,F10.1,2X,*FEE(UNITRECURRING)=*,F10.1,2X,*URTSC=*,F10.1)
    6 FORMAT(2X,*TOTAL NONRECURRING SUBSTSTEM DIRECT COSTS*,F10.1, 8X,
     1*TOTAL RECURRING SUBSYSTEM UNIT DIRECT COSTS*,F10.1)
    7 FORMAT(7F10.1)
   12 FORMAT( 8X,*NONRECURRING COST*,10F10.1)
   13 FORMAT( 7X,*UNITRECURRING COST*,10F10.1)
   18 FORMAT(10X,*N2H4 SUBSYSTEM NONREC COSTS=*,F10.1,4X,*N2H4 SUBSYSTEM
     1 URCOST=*,F10.1)
      DO 100 I = 1, 48
      READ(5,1) (XAMSAT(I),I=1,3),IMMD,STWT,TTCWT,PLWT,PWRKW,ACSWT
      READ(5,7) PWNH,ACSSUB,BOLP, TW, PW, PCPPU, PCPPN
      NRACSC=0.0
      URACSC=0.0
      NRSTC=1.1675*(632.56+23.08*(STWT**0.66))
      URSTC=1.1606*(54.19+0.93*(STWT**0.94))
      NRPLC=1.1675*(332.0*(PLWT**0.44))
```

(continued)

```
      IF(PLWT-230.0) 30,30,31
   30 URPLC= 1.1606*(7.77+4.83*PLWT)
      GO TO 34
   31 IF(PLWT-600.0) 32,32,33
   32 URPLC=970.0+1.430*PLWT
      GO TO 34
   33 URPLC=1570.0+).425*PLWT
   34 CONTINUE
      NRTTC=1.1675*(824.47+13.78*TTCWT)
      URTTC=1.1606*(-85.05+7.98*TTCWT)
      NRPWC=1.1675*(120.84*(PWRKW**0.45))
      URPWC=1.1606*(8.96*(PWRKW**0.63))
      IF(ACSWT.EQ.0.0)GO TO112
      NRACSC=1.1675*(1285.37+18.13*ACSWT)
      URACSC=1.1606*(62.78+7.35*ACSWT)  +0.001*PCNH*PWNH
      GO TO 113
  112 NRACSC=0.0
      URACSC=0.0
  113 CONTINUE
      X=NRACSC
      Y=URACSC
      II=IMMD-2
      GO TO (101,102,103,104,105),II
  101 AGEBL=AGEBLX
      AGENS=AGENSX
      GO TO 106
  102 AGEBL=1.050*AGEBLX
      AGENS=1.050*AGENSX
      GO TO 106
  103 AGEBL=1.083*AGEBLX
      AGENS=1.083*AGENSX
      GO TO 106
  104 CALL EXIT
      GO TO 106
  105 AGEBL=1.133*AGEBLX
      AGENS=1.133*AGENSX
```

(continued)

```
106 CONTINUE
    IF (I.GT.8) GO TO 11
    WRITE(6,10)
    WRITE(6,1)(XAMSAT(I),I=1,3),IMMD,STWT,TTCWT,PLWT,PWRKW,ACSWT
    NRACSC=1.0*NRACSC
    WRITE(6,2) NRSTC,NRTTC,NRPLC,NRPWC,NRACSC
    WRITE(6,3) URSTC,URTTC,URPLC,URPWC,URACSC
    NRTOTS=NRSTC+NRPLC+NRTTC=NRPWC+NRACSC+DISPN+AGEBL
    GO TO  15
 11 CONTINUE
    WRITE(6,100)
    WRITE(6,16) (XAMSAT(I),*=1,3),IMMD,STWT,TTCWT,PLWT,PWRKW,ACSWT,
   1ACSSUB ,BOLP,BOLP,TW,PW
    XNRT=1.1675*(1250.0+0.75*BOLP)
    URT=1.1606*(28.0+0.031*BOLP)
    XNRPC=1.1675*(1480.0+0.51*BOLP)
    URPC=1.1606*(70.0+0.06*BOLP)
    XNRPT=1.1675*(210.0+30.0*TW)
    URPT=1.1606*(0.63+1.14*TW)
    XNRP=PW*PCPPN *0.001
    URP=PW*PCPPU*0.001
    NRASUB=1.1675*(1285.37+18.13*ACSSUB)
    URASUB=1.1606*(62.78+7.35*ACSSUB)
    URACSC=URASUB+URT+URPC+URPT+URP+URACSC
    NRACSC=NRASUB+XNRT+XNRPC+XNRPT+XNRP+NRACSC
    NRTOTS=NRSTC+NRPLC+NRTTC+NRPWC+NRACSC+DISPN+AGENS
    WRITE(6,120 NRSTC,NRTTC,NRPLC,NRPWC,NRACSC,NRASUB,XNRT,XNRPC,XNRPT
   1,XNRP
    WRITE(6,13) URSTC,URTTC,URPLC,URPWC,URACSC,URASUB,URT,URPC,URPT,UR
   1P
 15 CONTINUE
    XNRSC =NRSTC+NRPLC+NRTTC+NRPWC+NRACSC
    XURSC =URSTC+URPLC+URTTC+URPWC+URACSC+
    WRITE(6,6) XNRSC,XURSC
```

(continued)

TABLE C3 (continued)

```
      WRITE(6,18)  X,  Y
      URTOTS=URSTC+URPLC+URTTC+URPWC+URACSC+DISPU
      NRPL=0.5*NRTOTS
      NRDC=1.5*NRTOTS
      NRBGA=0.82*NRDC
      FEE=0.10*(NRBGA+NRDC)
      NRTSC=NRBGA+NRDC+FEE
      WRITE(6,4) NRPL,NRDC,NRBGA,FEE,NRTSC
      URPL=0.3*URTOTS
      URLO=0.03*(URPL+URTOTS)
      URDC=URPL+URLO+URTOTS
      URBGA=1.06*URDC
      FEEU=(URDC+URBGA)*0.1
      URTSC=URDC+URBGA+FEEU
      WRITE(6,5) URPL,URLO,URDC,URBGA,FEEU,URTSC
  100 CONTINUE
      END COSTSAT
```

TEN-YEAR SYSTEM COSTS OF SATELLITES AS A FUNCTION OF NUMBER OF SATELLITES IN ORBIT, TYPE OF PROPULSION SUBSYSTEM AND MEAN MISSION DURATION

TABLES 1 THROUGH 6

Basic Cost Estimates

TABLES 7 THROUGH 12

Enhancement of MMD without Weight Penalty

TABLES 13 THROUGH 18

Cost of Satellites with Monopropellant Hydrazine Compared with the Cost of 7-Year Satellites with Electric Propulsion

ILLUSTRATIONS 1 THROUGH 6

Ten-Year Satellite System Costs as a Function of the Mean Mission Duration, Type of Propulsion Subsystem and Number of Satellites in Orbit

TABLE D1

COST OF SIX SMALL CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

I. Basic Cost Estimates (Costs in thousands of 1973 dollars)

						Satellite Recurring Cost			Launch Vehicle Cost		
Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Learning Curve Factor	Cumulative Avg. Cost	Total Recurring Sat. Cost	Nonrecurring Cost	Recurring Cost	Total System Cost
Mono. Hydrazine	3	25	12.5	55,859.8	11,770.7	0.8438	9,932.1	248,302.5	0.0	243,750.0	547,912.3
" "	4	20	10.0	58,661.0	12,581.5	0.8565	10,776.1	215,522.0		195,000.0	469,183.0
" "	5	17	8.5	61,535.8	13,501.8	0.8657	11,638.5	198,704.5		165,750.0	425,990.3
" "	7	13	6.5	65,617.0	14,817.3	0.8808	13,051.1	169,664.3		126,750.0	362,031.3
N_2H_4/Resistojet	3	25	12.5	55,294.7	11,557.6	0.8438	9,752.3	243,807.5	0.0	243,750.0	542,852.2
" "	4	20	10.0	58,067.5	12,356.8	0.8565	10,583.1	211,672.0		195,000.0	464,739.5
" "	5	17	8.5	60,876.2	13,250.3	0.8657	11,470.8	195,003.6		165,750.0	421,629.8
" "	7	13	6.5	64,853.1	14,523.2	0.8808	12,792.0	166,296.0		126,750.0	357,899.1
Cesium	3	25	12.5	69,856.6	11,572.1	0.8438	9,764.5	244,112.5	0.0	243,750.0	557,719.1
"	4	20	10.0	72,643.4	12,298.6	0.8565	10,533.8	210,676.0		195,000.0	478,319.4
"	5	17	8.5	75,238.9	13,040.6	0.8657	11,289.2	191,916.4		165,750.0	432,905.3
"	7	13	6.5	78,803.6	14,046.3	0.8808	12,372.0	160,836.0		126,750.0	366,389.6
N_2H_4/Cesium	3	25	12.5	73,655.4	11,780.7	0.8438	9,940.6	248,515.0	0.0	243,570.0	565,920.4
" "	4	20	10.0	76,431.7	12,495.5	0.8565	10,702.4	214,048.0		195,000.0	485,479.7
" "	5	17	8.5	79,102.2	13,273.5	0.8657	11,490.9	195,345.3		165,750.0	440,197.5
" "	7	13	6.5	82,782.3	14,333.5	0.8808	12,624.9	164,123.7		126,750.0	373,656.0
Colloid	3	25	12.5	67,516.1	10,915.4	0.8438	9,210.4	230,260.0	0.0	243,750.0	541,526.1
"	4	20	10.0	70,331.9	11,629.2	0.8565	9,960.4	199,208.0		195,000.0	464,539.9
"	5	17	8.5	72,749.6	12,297.3	0.8657	10,645.8	180,978.6		165,750.0	419,473.2
"	7	13	6.5	76,225.7	13,272.3	0.8808	11,690.2	151,972.6		126,750.0	354,948.3
N_2H_4/Colloid	3	25	12.5	72,500.1	11,436.9	0.8438	9,650.5	241,262.5	0.0	243,750.0	557,512.6
" "	4	20	10.0	75,249.5	12,131.9	0.8565	10,391.0	207,820.0		195,000.0	478,069.5
" "	5	16	8.5	77,903.5	12,888.9	0.8657	11,157.9	189,684.3		165,750.0	433,337.8
" "	7	13	6.5	81,572.1	13,912.8	0.8808	12,254.4	159,307.2		126,750.0	367,629.3

(continued)

TABLE D1 (continued)

COST OF SIX SMALL CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

I. Basic Cost Estimates (Costs in thousands of 1973 dollars)

						Satellite Recurring Cost			Launch Vehicle Cost		
Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Learning Curve Factor	Cumulative Avg. Cost	Total Recurring Sat. Cost	Nonrecurring Cost	Recurring Cost	Total System Cost
Mercury	3	25	12.5	68,267.3	11,141.3	0.8438	9,401.0	235,025.0	0.0	243,750.0	547,042.3
"	4	20	10.0	70,974.3	11,833.3	0.8565	10,135.2	202,704.0		195,000.0	468,678.3
"	5	17	8.5	73,447.5	12,534.9	0.8657	10,851.5	184,475.5		165,750.0	423,673.0
"	7	13	6.5	76,845.8	13,483.6	0.8808	11,876.4	154,399.2		126,570.0	357,995.0
N_2H_4/Mercury	3	25	12.5	72,730.6	11,520.7	0.8438	9,721.2	243,030.0	0.0	243,750.0	559,510.6
" "	4	20	10.0	75,399.1	12,194.2	0.8565	10,444.3	208,886.0		195,000.0	479,285.1
" "	5	17	8.5	78,053.4	12,970.3	0.8657	11,228.4	190,882.8		165,750.0	434,686.2
" "	7	13	6.5	81,559.2	13,965.6	0.8808	12,300.9	159,911.7		126,750.0	368,220.9
Ablative Teflon	3	25	12.5	70,789.1	11,816.3	0.8438	9,970.6	249,265.0	0.0	243,750.0	563,804.1
" "	4	20	10.0	73,546.0	12,531.6	0.8565	10,733.3	214,666.0		195,000.0	483,212.0
" "	5	17	8.5	76,161.9	13,294.7	0.8657	11,509.2	195,656.4		165,750.0	437,568.3
" "	7	13	6.5	79,708.7	14,309.6	0.8808	12,603.9	163,850.7		126,570.0	370,309.4
N_2H_4/Teflon	3	25	12.5	74,102.8	11,899.9	0.8438	10,041.1	251,027.5	0.0	243,750.0	568,880.3
" "	4	20	10.0	76,877.5	12,620.5	0.8565	10,809.5	216,190.0		195,000.0	488,067.5
" "	5	17	8.5	79,522.3	13,396.9	0.8657	11,597.7	197,160.9		165,750.0	442,433.2
" "	7	13	6.5	83,173.7	14,455.5	0.8808	12,732.4	165,521.2		126,750.0	375,444.9
MPD	3	25	12.5	70,031.4	11,675.7	0.8438	9,852.0	246,300.0	0.0	243,750.0	560,081.4
"	4	20	10.0	72,881.0	12,423.7	0.8565	10,640.9	212,818.0		195,000.0	480,699.0
"	5	17	8.5	75,518.7	13,191.6	0.8657	11,420.0	194,140.0		165,750.0	435,408.7
"	7	13	6.5	79,140.3	14,231.3	0.8808	12,534.9	162,953.7		126,750.0	368,844.0
N_2H_4/MPD	3	25	12.5	73,796.8	11,851.0	0.8438	9,999.9	249.997.5	0.0	243,750.0	567,544.3
" "	4	20	10.0	76,590.8	12,576.9	0.8565	10,772.1	215,442.0		195,000.0	487,032.8
" "	5	17	8.5	79,295.7	13,372.4	0.8657	11,576.5	196,800.5		165,750.0	441,846.2
" "	7	13	6.5	83,013.7	14,457.0	0.8808	12,733.7	165,538.1		126,750.0	375,301.8

TABLE D2

COST OF TWELVE SMALL CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

I. Basic Cost Estimates (Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LV s	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost
Mono. Hydrazine	3	50	25	55,859.8	11,770.7	0.8045	9,469.5	473,475.0	0.0	487,500.0	1,016,834.8
" " "	4	40	20	58,661.0	12,581.5	0.8171	10,280.3	411,212.0		390,000.0	859,873.0
" " "	5	34	17	61,535.8	13,501.8	0.8263	11,156.5	379,321.0		331,500.0	772,356.8
" " "	7	26	13	65,617.0	14,817.3	0.8416	12,470.2	324,225.2		253,500.0	643,342.2
N_2H_4/Resistojet	3	50	25	55,294.7	11,557.6	0.8045	9,298.1	464,905.0	0.0	487,500.0	1,007,699.7
" " "	4	40	20	58,067.5	12,356.8	0.8171	10,096.7	403,868.0		390,000.0	851,935.5
" " "	5	34	17	60,876.2	13,250.3	0.8263	10,948.7	372,255.8		331,500.0	764,632.0
" " "	7	26	13	64,853.1	14,523.2	0.8416	12,222.7	317,790.2		253,500.0	636,143.3
Cesium	3	50	25	69,856.6	11,572.1	0.8045	9,309.8	465,490.0	0.0	487,500.0	1,022,846.6
"	4	40	20	72,643.4	12,298.6	0.8171	10,049.2	401,968.0		390,000.0	864,611.4
"	5	34	17	75,238.9	13,040.6	0.8263	10,775.5	366,367.0		331,500.0	773,105.9
"	7	26	13	78,803.6	14,046.3	0.8416	11,821.4	307,356.4		253,500.0	639,660.0
N_2H_4/Cesium	3	50	25	73,655.4	11,780.7	0.8045	9,477.6	473,880.0	0.0	487,500.0	1,035,035.4
" "	4	40	20	76,431.7	12,495.5	0.8171	10,210.1	408,404.0		390,000.0	874,835.7
" "	5	34	17	79,102.2	13,273.5	0.8263	10,967.9	372,908.6		331,500.0	783,510.8
" "	7	26	13	82,782.3	14,333.5	0.8416	12,063.1	313,640.6		253,500.0	649,922.9
Colloid	3	50	25	67,516.1	10,915.4	0.8045	8,781.4	439,070.0	0.0	487,500.0	994,086.1
"	4	40	20	70,331.9	11,629.2	0.8171	9,502.2	380,088.0		390,000.0	840,419.9
"	5	34	17	72,749.6	12,297.3	0.8263	10,161.3	345,484.2		331,500.0	749,733.8
"	7	26	13	76,225.7	13,272.3	0.8416	11,170.0	290,420.0		253,500.0	620,145.7
N_2H_4/Colloid	3	50	25	72,500.1	11,436.9	0.8045	9,201.0	460,050.0	0.0	487,500.0	1,020,050.1
" "	4	40	20	75,249.5	12,131.9	0.8171	9,913.0	396,520.0		390,000.0	861,769.5
" "	5	34	17	77,903.5	12,888.9	0.8263	10,650.1	362,103.4		331,500.0	771,506.9
" "	7	26	13	81,572.1	13,912.8	0.8416	11,709.0	304,434.0		253,500.0	639,506.1

(continued)

TABLE D2 (continued)

COST OF TWELVE SMALL CATEGORY SATELLITES IN ORBIT FOR TEN YEARS
I. Basic Cost Estimates (Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs.	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost
Mercury	3	50	25	68,267.3	11,141.3	0.8045	8,963.2	448,160.0	0.0	487,500.0	1,003,927.3
"	4	40	20	70,974.3	11,833.3	0.8171	9,669.0	386,760.0		390,000.0	847,734.3
"	5	34	17	73,447.5	12,534.9	0.8263	10,357.6	352,158.4		331,500.0	757,105.9
"	7	26	13	76,845.8	13,483.6	0.8416	11,347.8	295,042.8		253,500.0	625,388.6
N_2H_4/Mercury	3	50	25	72,730.6	11,520.7	0.8045	9,268.4	463,420.0	0.0	487,500.0	1,023,650.6
" "	4	40	20	75,399.1	12,194.2	0.8171	9,963.9	398,556.0		390,000.0	863,955.1
" "	5	34	17	78,053.4	12,970.3	0.8263	10,717.4	364,391.6		331,500.0	773,945.0
" "	7	26	13	81,559.2	13,965.6	0.8416	11,75[illegible].5	305,591.0		253,500.0	640,650.2
Ablative Teflon	3	50	25	70,789.1	11,816.3	0.8045	9,506.2	475,310.7	0.0	487,500.0	1,033,599.8
" "	4	40	20	73,546.0	12,531.6	0.8171	10,239.6	409,582.8		390,000.0	873,128.8
" "	5	34	17	76,161.9	13,294.7	0.8263	10,985.4	373,504.0		331,500.0	781,165.9
" "	7	26	13	79,708.7	14,309.6	0.8416	12,043.0	313,116.9		253,500.0	646,325.6
N_2H_4/Teflon	3	50	25	74,102.8	11,899.9	0.8045	9,573.5	478,673.5	0.0	487,500.0	1,040,276.3
" "	4	40	20	76,877.5	12,620.5	0.8171	10,312.2	412,488.4		390,000.0	879,365.9
" "	5	34	17	79,522.3	13,396.9	0.8263	11,069.9	376,375.2		331,500.0	787,397.5
" "	7	26	13	83,173.7	14,455.5	0.8416	12,165.8	316,309.5		253,500.0	652,983.2
MPD	3	50	25	70,031.4	11,675.7	0.8045	9,393.1	469,655.0	0.0	487,500.0	1,027,186.4
"	4	40	20	72,881.0	12,423.7	0.8171	10,151.4	406,056.2		390,000.0	869,337.2
"	5	34	17	75,518.7	13,191.6	0.8263	10,900.2	370,607.5		331,500.0	777,626.2
"	7	26	13	79,140.3	14,231.3	0.8416	11,977.1	311,403.6		253,500.0	644,043.9
N_2H_4/MPD	3	50	25	73,796.8	11,851.0	0.8045	9,534.1	476,706.5	0.0	487,500.0	1,038,003.3
" "	4	40	20.	76,590.8	12,576.9	0.8161	10,276.6	411,063.4		390,000.0	877,654.2
" "	5	34	17	79,295.7	13,372.4	0.8263	11,049.6	375,686.9		331,500.0	786,482.6
" "	7	26	13	83,013.7	14,457.0	0.8416	12,167.0	316,342.3		253,500.0	652,656.0

TABLE D3

COST OF SIX MEDIUM CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

I. Basic Cost Estimates (Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LV s	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost
Mono. Hydrazine	3	25	25	72,896.1	17,824.5	0.8438	15,040.3	376,007.8	0.0	487,500.0	936,403.9
" " "	4	20	20	76,975.6	18,855.6	0.8565	16,149.8	322,996.4		390,000.0	789,972.0
" " "	5	17	17	81,197.5	20,192.3	0.8657	17,480.5	297,168.1		331,500.0	709,865.6
" " "	7	13	13	87,151.8	22,097.1	0.8808	19,463.1	253,020.6		253,500.0	593,672.4
N_2H_4/Resistojet	3	25	25	72,973.8	17,856.2	0.8438	15,067.1	376,676.5	0.0	487,500.0	937,150.3
" " "	4	20	20	77,026.9	18,876.5	0.8565	16,167.7	323,354.4		390.000.0	790,381.3
" " "	5	17	17	81,255.0	20,215.6	0.8657	17,500.7	297,511.0		331,500.0	710,266.0
" " "	7	13	13	87,203.5	22,119.5	0.8808	19,482.9	253,277.1		253,500.0	593,980.6
Cesium	3	25	25	87,066.3	17,490.5	0.8438	14758.5	368,962.1	0.0	487,500.0	943,528.4
"	4	20	20	90,991.1	18,365.5	0.8565	15,730.1	314,601.0		390,000.0	795,592.1
"	5	17	17	94,749.6	19,446.5	0.8657	16,834.8	286,192.2		331,500.0	712,441.8
"	7	13	13	99,882.0	20,909.5	0.8808	18,417.1	239,422.1		253,500.0	592,804.1
N_2H_4/Cesium	3	25	25	91,464.4	17,905.3	0.8438	15,108.5	377,712.3	0.0	487,500.0	956,676.7
" "	4	20	20	95,405.0	18,783.7	0.8565	16,088.2	321,764.8		390,000.0	807,169.8
" "	5	17	17	99,318.7	19,932.4	0.8657	17,255.5	293,343.1		331,500.0	724,161.8
" "	7	13	13	104,689.3	21,495.1	0.8808	18,932.9	246,127.5		253,500.0	604,316.8
Colloid	3	25	25	84,332.1	16,719.8	0.8438	14,108.2	352,704.2	0.0	487,500.0	924,536.3
"	4	20	20	88,201.7	17,549.0	0.8565	15,030.7	300,614.4		390,000.0	778,816.1
"	5	17	17	91,902.2	18,582.3	0.8657	16,086.7	273,473.9		331,500.0	696,876.1
"	7	13	13	96,995.6	19,974.6	0.8808	17,593.6	228,717.2		253,500.0	579,212.8
N_2H_4/Colloid	3	25	25	89,576.3	17,352.8	0.8438	14,642.3	366,057.3	0.0	487.500.0	943,123.6
" "	4	20	20	93,496.3	18,203.1	0.8565	15,591.0	311,819.1		390,000.0	795,315.4
" "	5	17	17	97,411.6	19,312.9	0.8657	16,719.2	284,226.0		331,500.0	713,137.6
" "	7	13	13	102,760.5	20,818.6	0.8808	18,337.0	238,381.3		253,500.0	594,641.8

(continued)

TABLE D3 (continued)

COST OF SIX MEDIUM CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

I. Basic Cost Estimates (Costs in thousands of 1973 dollars)

						Satellite Recurring Cost			Launch Vehicle Cost		
Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Learning Curve Factor	Cumulative Avg. Cost	Total Recurring Sat. Cost	Nonrecurring Cost	Recurring Cost	Total System Cost
Mercury	3	25	25	84,847.4	16,864.1	0.8438	14,229.9	355,748.2	0.0	487,500.0	928,095.6
"	4	20	20	88,616.6	17,682.3	0.8565	15,144.9	302,897.8		390,000.0	781,514.4
"	5	17	17	92,194.2	18,699.3	0.8657	16,188.0	275,195.7		331,500.0	698.889.9
"	7	13	13	97,092.0	20,074.6	C.8808	17,681.7	229,862.2		253,500.0	580,454.2
N_2H_4/Mercury	3	25	25	89,976.1	17,484.9	0.8438	14,753.8	368,844.0	0.0	487,500.0	946,320.1
" "	4	20	20	93,809.7	18,330.2	0.8565	15,699.8	313,996.3		390.000.0	797,806.0
" "	5	17	17	97,621.0	19,431.9	0.8657	16,822.2	285,977.3		331,500.0	715,098.3
" "	7	13	13	102,805.4	20,930.7	0.8808	18,435.8	239,664.9		253,500.0	595,970.3
Ablative Teflon	3	25	25	88,824.9	18,016.9	0.8438	15,202.7	380,066.5	0.0	487,500.0	956,391.4
" "	4	20	20	92,792.5	18,924.5	0.8565	16,208.8	324,176.7		390,000.0	806,969.2
" "	5	17	17	96,611.3	20,044.8	0.8657	17,352.8	294,997.3		331,500.0	723,108.6
" "	7	13	13	101,800.4	21,553.4	0.8808	18,984.2	246,795.1		253,500.0	602,095.5
N_2H_4/Teflon	3	25	25	87,195.3	16,322.2	0.8438	13,772.7	344,316.8	0.0	487,500.0	919,012.1
" "	4	20	20	91,307.4	17,271.2	0.8565	14,792.8	295,855.7		390,000.0	777,163.1
" "	5	17	17	95,240.3	18,433.9	0.8657	15,958.2	271,289.9		331,500.0	698,030.2
" "	7	13	13	100,573.8	19,994.5	0.8808	17,611.2	228,945.0		253,500.0	583,018.8
MPD	3	25	25	87,262.2	17,622.7	0.8438	14,870.C	371,750.9	0.0	487,500.C	946,513.1
"	4	20	20	91,234.7	18,525.3	0.8565	15,866.9	317,338.4		390,000.0	798,573.1
"	5	17	17	95,013.6	19,623.8	0.8657	16,988.3	288,801.5		331,500.0	715,315.1
"	7	13	13	100,270.8	21,155.5	0.8808	18,633.8	242,238.9		253,500.0	596,009.7
N_2H_4/MPD	3	25	25	91,544.9	17,969.3	0.8438	15,162.5	379,062.4	0.0	487,500.0	958,107.3
" "	4	20	20	95,502.5	18,865.8	0.8565	16,158.6	323,171.2		390,000.0	808,673.7
" "	5	17	17	99,470.5	20,037.4	0.8657	17,346.4	294,888.4		331,500.0	725,858.9
" "	7	13	13	104,892.8	21,629.5	0.8808	19,051.3	247,666.4		253,500.0	606,059.2

TABLE D4

COST OF TWELVE MEDIUM CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

I. Basic Cost Estimates (Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost
Mono. Hydrazine	3	50	50	72,896.1	17,824.5	0.8045	14,339.8	716,990.5	0.0	975,000.0	1,764,886.6
" "	4	40	40	76,975.6	18,855.6	0.8171	15,406.9	616,276.4		780,000.0	1,473,252.0
" "	5	34	34	81,197.5	20,192.3	0.8263	16,684.9	567,286.5		663,000.0	1,311,484.0
" "	7	26	26	87,151.8	22,097.1	0.8416	18,596.9	483,519.9		507,000.0	1,077,671.7
N_2H_4/Resistojet	3	50	50	72,973.9	17,856.2	0.8045	14,365.3	718,265.7	0.0	975,000.0	1,766,239.5
" "	4	40	50	77,026.9	18,876.5	0.8171	15,424.0	616,959.5		780,000.0	1,473,986.4
" "	5	34	34	81,255.0	20,215.6	0.8263	16,704.2	567,941.1		663,000.0	1,312,196.1
" "	7	26	26	87,203.5	22,119.5	0.8416	18,615.8	484,010.1		507,000.0	1,078,213.6
Cesium	3	50	50	87,066.3	17,490.5	0.8045	14,071.1	703,555.4	0.0	975,000.0	1,765,621.7
"	4	40	40	90,991.1	18,365.5	0.8171	15,006.5	600,258.0		780.000.0	1,471,249.1
"	5	34	34	94,749.6	19,446.5	0.8263	16,068.6	546,333.9		663,000.0	1,304,083.5
"	7	26	26	99,882.0	20,909.5	0.8416	17,597.4	457,533.3		507,000.0	1,064,415.3
N_2H_4/Cesium	3	50	50	91,464.4	17,905.3	0.9045	14,404.8	720,240.7	0.0	975,000.0	1,786,705.1
" "	4	40	40	95,405.0	18,783.7	0.8171	15,348.2	613,926.5		780,000.0	1,489,331.5
" "	5	34	34	99,318.7	19,932.4	0.8263	16,470.1	559,984.8		663,000.0	1,322,303.5
" "	7	26	26	104,689.3	21,495.1	0.8416	18,090.3	470,347.2		507,000.0	1,082,036.5
Colloid	3	50	50	84,332.1	16,719.8	0.8045	13,451.1	672,554.0	0.0	975,000.0	1,731,886.1
"	4	40	40	88,201.7	17,549.0	0.8171	14,339.3	573,571.5		780,000.0	1,441,773.2
"	5	34	34	91,902.2	18,582.3	0.8263	15,354.6	522,054.9		663,000.0	1,276,957.1
"	7	26	26	96,995.6	19,974.6	0.8416	16,810.6	437,076.2		507,000.0	1,041,071.8
N_2H_4/Colloid	3	50	50	89,576.3	17,352.8	0.8045	13,960.3	698,016.4	0.0	975,000.0	1,762,592.7
" "	4	40	40	93,496.3	18,203.1	0.8171	14,873.8	594,950.1		780,000.0	1,468,446.4
" "	5	34	34	97,411.6	19,312.9	0.8263	15,958.3	542,580.5		663,000.0	1,302,992.1
" "	7	26	26	102,760.5	20,818.6	0.8416	17,520.9	455,544.3		507,000.0	1,065,304.8

(continued)

TABLE D4 (continued)

COST OF TWELVE MEDIUM CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

I. Basic Cost Estimates (Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost
Mercury	3	50	50	84,847.4	16,864.1	0.8045	13,567.2	678,358.4	0.0	975,000.0	1,738,205.8
"	4	40	40	88,616.6	17,682.3	0.8171	14,448.2	577,928.3		780,000.0	1,446,544.9
"	5	34	34	92,194.2	18,699.3	0.8263	15,451.2	525,341.9		663,000.0	1,280,536.1
"	7	26	26	97,092.0	20,074.6	0.8416	16,894.8	439,264.4		507,000.0	1,043,356.4
N_2H_4/Mercury	3	50	50	89,976.1	17,484.9	0.8045	14,066.6	703,330.1	0.0	975,000.0	1,768,306.2
" "	4	40	40	93,809.7	18,330.2	0.8171	14,977.6	599,104.3		780,000.0	1,472,914.0
" "	5	34	34	97,621.0	19,431.9	0.8263	16,056.6	545,923.7		663,000.0	1,306,544.7
" "	7	26	26	102,805.4	20,930.7	0.8416	17,615.3	457,997.2		507,000.0	1,067,802.6
Ablative Teflon	3	50	50	88,824.9	18,016.9	0.8045	14,494.6	724,729.8	0.0	975,000.0	1,788,554.7
" "	4	40	40	92,792.5	18,924.5	0.8171	15,463.2	618,528.4		780,000.0	1,491,320.9
" "	5	34	34	96,611.3	20,044.8	0.8263	16,563.0	563,142.6		663,000.0	1,322,753.9
" "	7	26	26	101,800.4	21,553.4	0.8416	18,139.3	471,622.9		507,000.0	1,080,423.3
N_2H_4/Teflon	3	50	50	87,195.3	16,322.2	0.8045	13,131.2	656,560.5	0.0	975,000.0	1,718,755.8
" "	4	40	40	91,307.4	17,271.2	0.8171	14,112.3	564,491.9		780,000.0	1,435,799.3
" "	5	34	34	95,240.3	18,433.9	0.8263	15,231.9	517,885.7		663,000.0	1,276,126.0
" "	7	26	26	100,573.8	19,994.5	0.8416	16,827.4	437,511.7		507,000.0	1,045,085.5
MPD	3	50	50	87,262.2	17,622.7	0.8045	14,177.5	708,873.1	0.0	975,000.0	1,771,135.3
"	4	40	40	91,234.7	18,525.3	0.8171	15,137.0	605,480.9		780,000.0	1,476,715.6
"	5	34	34	95,013.6	19,623.8	0.8263	16,215.2	551,315.0		663,000.0	1,309,328.6
"	7	26	26	100,270.8	21,155.5	0.8416	17,804.5	462,916.2		507,000.0	1,070,187.0
N_2H_4/MPD	3	50	50	91,544.9	17,969.3	0.8045	14,456.3	722,815.1	0.0	975,000.0	1,789,360.0
"	4	40	40	95,502.5	18,865.8	0.8171	15,415.3	616,609.8		780,000.0	1,492,112.3
"	5	34	34	99,470.5	20,037.4	0.8263	16,556.9	562,934.7		663,000.0	1,325,405.2
"	7	26	26	104,892.8	21,629.5	0.8416	18,203.4	473,288.1		507,000.0	1,085,180.9

TABLE D5

COST OF SIX LARGE CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

I. Basic Cost Estimates (Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satel-lites	No. of LVs	Satellite Nonrecur-ring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonre-curring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost
Mono. Hydrazine	3	25	25	85,637.8	21,552.1	0.8438	18,160.3	454,008.7	0.0	487,500.0	1,027,146.5
" " "	4	20	20	90,813.0	22,839.2	0.8565	19,561.8	391,235.5	6,000.0	400,000.0	888,048.5
" " "	5	17	17	96,129.5	24,596.6	0.8657	21,293.3	361,985.7	9,500.0	340,000.0	807,615.2
" " "	7	13	13	103,594.5	27,086.5	0.8808	23,857.8	310,151.3	10,000.0	273,000.0	696,745.8
N_2H_4/Resistojet	3	25	25	86,093.9	21,707.9	0.8438	18,317.1	457,928.2	0.0	487,500.0	1,031,522.1
" "	4	20	20	91,262.4	23,022.3	0.8565	19,718.6	394,372.0	6,000.0	400,000.0	891,634 4
" "	5	17	17	96,636.0	24,802.9	0.8657	21,471.9	365,021.8	9,500.0	340,000.0	811,157.8
" "	7	13	13	104,193.2	27,330.5	0.8808	24,072.7	312,945.2	10,000.0	273,000.0	700,138.4
Cesium	3	25	25	99,920.0	21,017.8	0.8438	17,734.8	443,370.5	0.0	487,500.0	1,030,790.5
"	4	20	20	104,798.8	22,118.3	0.8565	18,944.3	378,886.5	0.0	390,000.0	873,685.3
"	5	17	17	109,504.5	23,553.1	0.8657	20,389.9	346,628.6	6,000.0	340,000.0	802,133.1
"	7	13	13	115,886.8	25,480.2	0.8808	22,443.0	291,759.0	9,500.0	260,000.0	677,145.8
N_2H_4/Cesium	3	25	25	104,758.4	21,594.8	0.8438	18,221.7	455,542.3	0.0	487,500.0	1,047,800.7
" "	4	20	20	109,694.7	22,715.4	0.8565	19,455.7	389,114.8	0.0	390,000.0	888,809.5
" "	5	17	17	114,596.2	24,238.6	0.8657	20,983.4	356,717.1	6,000.0	340,000.0	817,313.3
" "	7	13	13	121,311.5	26,299.7	0.8808	23,164.8	301,142.1	6,000.0	260,000.0	688,453.6
Colloid	3	25	25	97,092.2	20,128.4	0.8438	16,984.3	424,608.6	0.0	487,500.0	1,009,200.8
"	4	20	20	101,534.6	21,164.7	0.8565	18,127.6	362,551.3	0.0	390,000.0	854,085.9
"	5	17	17	106,180.2	22,540.6	0.8657	19,513.4	331,727.8	6,000.0	340,000.0	783,908.0
"	7	13	13	112,550.9	24,386.7	0.8808	21,479.8	279,237.5	6,000.0	260,000.0	657,788.4
N_2H_4/Colloid	3	25	25	102,173.3	20,845.2	0.8438	17,589.2	439,729.5	0.0	487,500.0	1,029,402.8
" "	4	20	20	107,066.8	21,918.2	0.8565	18,772.9	375,458.8	0.0	390,000.0	872,525.6
" "	5	17	17	111,933.7	23,385.1	0.8657	20,244.5	344,156.2	6,000.0	340,000.0	802,089.9
" "	7	13	13	118,605.0	25,363.1	0.8808	22,339.8	290,417.6	6,000.0	260,000.0	675,022.6

(continued)

TABLE D5 (continued)

COST OF SIX LARGE CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

1. Basic Cost Estimates (Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost
Mercury	3	25	25	97,550.7	20,387.5	0.8438	17,203.0	430,074.3	0.0	487,500.0	1,015,125.0
"	4	20	20	102,290.1	21,433.6	0.8565	18,357.9	367,157.6	0.0	390,000.0	859,447.7
"	5	17	17	106,820.4	22,808.7	0.8657	19,745.5	335,673.4	6,000.0	340,000.0	788,493.8
"	7	13	13	112,953.1	24,651.2	0.8808	21,712.8	282,266.1	6,000.0	260,000.0	661,219.2
N_2H_4/Mercury	3	25	25	102,736.3	21,023.4	0.8438	17,739.5	443,488.6	0.0	487,500.0	1,033,724.9
" " "	4	20	20	107,525.6	22,095.7	0.8565	18,925.0	378,499.3	0.0	390,000.0	876,024.9
" " "	5	17	17	112,286.7	23,557.1	0.8657	20,393.4	346,687.5	6,000.0	340,000.0	804,974.2
" " "	7	13	13	118,732.7	25,526.3	0.8808	22,483.6	292,286.4	6,000.0	260,000.0	677,019.1
Ablative Teflon	3	25	25	100,937.1	21,282.9	0.8438	17,958.5	448,962.5	0.0	487,500.0	1,037,399.6
" " "	4	20	20	107,013.9	22,809.2	0.8565	19,536.1	390,722.0	6,000.0	400,000.0	903,735.9
" " "	5	17	17	111,780.0	24,289.4	0.8657	21,027.3	357,464.7	6,000.0	340,000.0	815,244.7
" " "	7	13	13	118,218.8	26,273.1	0.8808	23,141.4	300,837.5	9,500.0	260,000.0	688,556.3
N_2H_4/Teflon	3	25	25	106,162.5	21,998.2	0.8438	18,562.1	464,052.5	0.0	487,500.0	1,057,715.0
" "	4	20	20	111,127.8	23,144.5	0.8565	19,823.3	396,466.0	6,000.0	400,000.0	913,593.8
" "	5	17	17	116,049.0	24,685.2	0.8657	21,370.0	363,289.6	6,000.0	340,000.0	825,338.6
" "	7	13	13	122,753.4	26,769.1	0.8808	23,578.2	306,516.9	9,500.0	260,000.0	696,770.3
MPD	3	25	25	100,119.1	21,180.0	0.8438	17,871.7	446,792.5	0.0	487,500.0	1,034,411.6
"	4	20	20	105,070.7	22,319.0	0.8565	19,116.2	382,324.0	6,000.0	400,000.0	893,394.7
"	5	17	17	109,831.2	23,794.2	0.8657	20,598.6	350,176.9	6,000.0	340,000.0	806,008.1
"	7	13	13	116,312.9	25,789.6	0.8808	22,715.5	295,301.2	9,500.0	260,000.0	681,114.1
N_2H_4/MPD	3	25	25	104,752.2	21,654.1	0.8538	18,271.7	456,792.5	0.0	487,500.0	1,049,044.7
" "	4	20	20	109,726.1	22,797.8	0.8565	19,526.3	390,526.0	6,000.0	400,000.0	906,252.1
" "	5	17	17	114,690.1	24,343.8	0.8657	21,074.4	358,265.3	6,000.0	340,000.0	818,955.4
" "	7	13	13	121,453.2	26,448.7	0.8808	23,296.0	302,848.2	9,500.0	260,000.0	693,801.4

TABLE D6

COST OF TWELVE LARGE CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

I. Basic Cost Estimates (Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost
Mono. Hydrazine	3	50	50	85,637.8	21,522.1	0.8045	17,314.5	865,726.5	0.0	975,000.0	1,926,364.3
" " "	4	40	40	90,813.0	22,839.2	0.8171	18,661.9	746,476.4	6,000.0	800,000.0	1,643,289.4
" " "	5	34	34	96,129.5	24,596.6	0.8263	20,324.2	691,021.8	9,500.0	680,000.0	1,476,651.3
" " "	7	26	26	103,594.5	27,086.5	0.8416	22,796.0	592,696.0	10,000.0	546,000.0	1,252,290.5
N_2H_4/Resistojet	3	50	50	86,093.9	21,707.9	0.8045	17,464.0	873,200.3	0.0	975,000.0	1,934,294.2
" "	4	40	40	91,262.4	23,022.3	0.8171	18,811.5	752,460.9	6,000.0	800,000.0	1,649,723.3
" "	5	34	34	96,636.0	24,802.9	0.8263	20,494.6	696,817.6	9,500.0	680,000.0	1,482,953.6
" "	7	26	26	104,193.2	27,330.5	0.8416	23,001.3	598,035.1	10,000.0	546,000.0	1,258,228.3
Cesium	3	50	50	99,920.0	21,017.8	0.8045	16,908.8	845,441.0	0.0	975,000.0	1,920,361.0
"	4	40	40	104,798.8	22,118.3	0.8171	18,072.9	722,914.5	0.0	780,000.0	1,607,713.3
"	5	34	34	109,504.5	23,553.1	0.8263	19,461.9	661,705.5	6,000.0	680,000.0	1,457,210.0
"	7	26	26	115,[illegible]86.8	25,480.2	0.8416	21,444.1	557,547.5	9,500.0	520,000.0	1,202,934.3
N_2H_4/Cesium	3	50	50	104,758.4	21,594.4	0.8045	17,372.7	868,634.7	0.0	975,000.0	1,948,393.1
" "	4	40	40	109,694.7	22,715.4	0.8171	18,560.8	742,430.1	0.0	780,000.0	1,632,124.8
" "	5	34	34	114,596.2	24,238.6	0.8263	20,028.4	680,964.1	6,000.0	680,000.0	1,481,560.3
" "	7	26	26	121,311.5	26,299.7	0.8416	22,133.8	575,479.5	6,000.0	520,000.0	1,222,791.0
Colloid	3	50	50	97,092.2	20,128.4	0.8045	16,193.3	809,664.9	0.0	975,000.0	1,881,757.1
"	4	40	40	101,534.6	21,164.7	0.8171	17,293.7	691,747.1	0.0	780,000.0	1,573,281.7
"	5	34	34	106,180.2	22,540.6	0.8263	18,625.3	633,260.1	6,000.0	680,000.0	1,425,440.3
"	7	26	26	112,550.9	24,386.7	0.8416	20,523.8	533,620.0	6,000.0	520,000.0	1,172,170.9
N_2H_4/Colloid	3	50	50	102,173.3	20,845.2	0.8045	16,770.0	838,498.2	0.0	975,000.0	1,915,671.5
" "	4	40	40	107,066.8	21,918.2	0.8171	17,909.4	716,374.5	0.0	780,000.0	1,603,441.3
" "	5	34	34	111,933.7	23,385.1	0.8263	19,323.1	656,985.7	6,000.0	680,000.0	1,454,919.4
" "	7	26	26	118,605.0	25,363.1	0.8416	21,345.6	554,985.2	6,000.0	520,000.0	1,199,590.2

(continued)

TABLE D6 (continued)

COST OF TWELVE LARGE CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

I. Basic Cost Estimates (Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost
Mercury	3	50	50	97,550.7	20,387.5	0.8045	16,401.7	820,087.2	0.0	975,000.0	1,892,637.9
"	4	40	40	102,290.1	21,433.6	0.8171	17,513.4	700,535.8	0.0	780,000.0	1,582,825.9
"	5	34	34	106,820.4	22,808.7	0.8263	18,846.8	640,792.2	6,000.0	680,000.0	1,433,612.6
"	7	26	26	112,953.1	24,651.2	0.8416	20,746.5	539,407.7	6,000.0	520,000.0	1,178,360.8
N_2H_4/Mercury	3	50	50	102,736.3	21,023.4	0.8045	16,913.3	845,666.3	0.0	975,000.0	1,923,402.6
" "	4	40	40	107,525.6	22,095.7	0.8171	18,054.4	722,175.9	0.0	780,000.0	1,609,701.5
" "	5	34	34	112,286.7	23,557.1	0.8263	19,465.2	661,817.9	6,000.0	680,000.0	1,460,104.6
" "	7	26	26	118,732.7	25,526.3	0.8416	21,482.9	558,556.3	6,000.0	520,000.0	1,203,289.0
Ablative Teflon	3	50	50	100,937.1	21,282.9	0.8045	17,122.1	856,104.7	0.0	975,000.0	1,932,041.8
" "	4	40	40	107,013.9	22,809.2	0.8171	18,637.4	745,495.9	6,000.0	800,000.0	1,658,509.8
" "	5	34	34	111,780.0	24,289.4	0.8263	20,070.3	682,391.3	6,000.0	680,000.0	1,480,171.3
" "	7	26	26	118,218.8	26,273.1	0.8416	22,111.4	574,897.5	9,500.0	520,000.0	1,222,616.3
N_2H_4/Teflon	3	50	50	106,162.5	21,998.2	0.8045	17,697.6	884,877.6	0.0	975,000.0	1,966,040.1
" "	4	40	40	111,127.8	23,144.5	0.8171	18,911.4	756,454.8	6,000.0	800,000.0	1,673,582.6
" "	5	34	34	116,049.0	24,685.2	0.8263	20,397.4	693,511.0	6,000.0	680,000.0	1,495,560.0
" "	7	26	26	122,753.4	26,769.1	0.8416	22,528.9	585,750.7	9,500.0	520,000.0	1,238,004.1
MPD	3	50	50	100,119.1	21,180.0	0.8045	17,039.3	851,965.5	0.0	975,000.0	1,927,084.6
"	4	40	40	105,070.7	22,319.0	0.8171	18,236.9	729,474.2	6,000.0	800,000.0	1,640,544.9
"	5	34	34	109,831.2	23,794.2	0.8263	19,661.2	668,479.0	6,000.0	680,000.0	1,464,310.2
"	7	26	26	116,312.9	25,789.6	0.8416	21,704.5	564,317.7	9,500.0	520,000.0	1,210,130.6
N_2H_4/MPD	3	50	50	104,752.2	21,654.1	0.8045	17,420.7	871,036.2	0.0	975,000.0	1,950,788.4
" "	4	40	40	109,726.1	22,797.8	0.8171	18,628.1	745,123.3	6,000.0	800,000.1	1,660,849.4
" "	5	34	34	114,690.1	24,343.8	0.8263	19,661.2	683,919.6	6,000.0	680,000.0	1,484,609.7
" "	7	26	26	121,453.2	26,448.7	0.8416	22,259.2	578,739.9	9,500.0	520,000.0	1,229,693.1

TABLE D7

COST OF SIX SMALL CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

II. Enhancement of MMD without Weight Penalty (all satellites weigh 1,000 pounds)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Cumulative Avg. Cost	Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Recurring Cost	Total System Cost	Percent Improvement
Mono. Hydrazine	3.00	25	12.5	55,859.8	11,770.7	0.8438	9,932.1	248,302.5	0.0	243,750.0	547,912.3	0.0
N_2H_4/Resistojet	3.28	24	12.0	56,071.1	11,781.4	0.8461	9,968.2	239,237.3	0.0	234,000.0	529,308.4	3.4
Cesium	3.53	22	11.0	71,333.6	11,957.2	0.8511	10,176.7	223,888.0	0.0	214,500.0	509,721.6	7.0
N_2H_4/Cesium	4.05	20	10.0	76,565.2	12,534.4	0.8565	10,735.7	214,714.3	0.0	195,000.0	486,279.5	11.2
Colloid	4.68	18	9.0	71,975.9	12,083.5	0.8625	10,422.0	187,596.5	0.0	175,500.0	435,072.4	20.6
N_2H_4/Colloid	4.52	18	9.0	76,629.6	12,525.5	0.8625	10,803.3	194,459.0	0.0	175,500.0	446,588.6	18.5
Mercury	4.60	18	9.0	72,458.2	12,254.3	0.8625	10,569.3	190,247.4	0.0	175,500.0	438,205.6	20.0
N_2H_4/Mercury	4.60	18	9.0	76,991.7	12,659.9	0.8625	10,919.2	196,545.6	0.0	175,500.0	449,037.3	18.0
Ablative Teflon	3.28	24	12.0	71,561.0	12,016.6	0.8461	10,167.2	244,013.6	0.0	234,000.0	549,574.6	-0.3
N_2H_4/Teflon	3.84	21	10.5	76,433.6	12,505.2	0.8537	10,675.7	224,189.5	0.0	204,750.0	505,373.1	7.8
MPD	2.94	26	13.0	69,860.4	11,630.8	0.8416	9,788.5	254,501.0	0.0	253,500.0	577,861.4	-5.5
N_2H_4/MPD	3.75	22	11.0	75,892.3	12,395.4	0.8511	10,549.8	232,094.4	0.0	214,500.0	522,486.7	4.6

TABLE D8

COST OF TWELVE SMALL CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

II. Enhancement of MMD without Weight Penalty (all satellites weigh 1,000 pounds)

Type of Propulsion Subsystem	MMD (Years)	No. of Satel-lites	No. of LVs	Satellite Nonrecur-ring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonre-curring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost	Percent Improve-ment
Mono. Hydrazine	3.00	50	[illegible]	55,859.8	11,770.7	0.8045	9,469.5	473,475.0	0.0	487,500.0	1,016,834.8	0.0
N_2H_4/Resistojet	3.28	48	24	56,071.1	11,781.4	0.8068	9,505.2	456,251.2	0.0	468,000.0	980,322.3	3.6
Cesium	3.53	44	22	71,333.6	11,957.2	0.8117	9,705.7	427,049.0	0.0	429,000.0	927,382.6	8.8
N_2H_4/Cesium	4.05	40	20	76,565.2	12,534.4	0.8171	10,241.9	409,674.3	0.0	390,000.0	876,239.5	13.8
Colloid	4.68	36	18	[illegible],975.9	12,083.5	0.8231	9,945.9	358.053.4	0.0	351,000.0	781,029.3	23.2
N_2H_4/Colloid	4.52	36	18	76,629.6	12.525.5	0.8231	10,309.7	371,150.6	0.0	351,000.0	798,780.2	21.4
Mercury	4.6	36	18	[illegible]2,458.2	12,254.3	0.8231	10,086.5	363,114.5	0.0	351,000.0	786,572.7	22.6
N_2H_4/Mercury	4.6	36	18	76,991.7	12,659.9	0.8231	10,420.4	375,134.4	0.0	351,000.0	803,126.1	21.0
Ablative Teflon	3.28	48	24	71,561.0	12,016.6	0.8068	9,695.0	465,359.7	0.0	468,000.0	1,004,920.7	1.2
N_2H_4/Teflon	3.84	42	21	76,433.6	12,505.2	0.8143	10,183.0	427,685.3	0.0	409,500.0	913,618.9	10.2
MPD	2.94	52	26	69,860.4	11,630.8	0.8023	9,331.4	485,232.3	0.0	507,000.0	1,062,092.7	-4.5
N_2H_4/MPD	3.75	44	22	75,892.3	12,395.4	0.8117	10,061.3	442,699.2	0.0	429,000.0	947,591.5	6.8

TABLE D9

COST OF SIX MEDIUM CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

II. Enhancement of MMD without Weight Penalty (all satellites weigh 2,000 pounds)

Type of Propulsion Subsystem	MMD (years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Cumulative Avg. Cost	Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Recurring Cost	Total System Cost	Percent Improvement
Monc. Hydrazine	3.00	25	25	72,896.1	17,824.5	0.8438	15,040.3	376,007.8	0.0	487,500.0	936,403.9	0.0
N_2H_4/Resistojet	3.07	25	25	73,257.5	17,927.6	0.8438	15,127.3	378,183.2	0.0	487,500.0	938,940.7	-0.3
Cesium	3.60	22	22	89,421.2	18,015.5	0.8511	15,333.0	337,325.8	0.0	429,000.0	855,747.0	8.6
N_2H_4/Cesium	3.70	22	22	94,222.8	18,520.2	0.8511	15,762.5	346,775.6	0.0	429,000.0	869,998.4	7.1
Colloid	4.26	19	19	89,163.8	17,817.7	0.8594	15,312.5	290,937.4	0.0	370,500.0	750,601.2	19.8
N_2H_4/Colloid	4.06	20	20	93,731.2	18,269.7	0.8565	15,648.0	312,959.8	0.0	390,000.0	796,691.0	14.9
Mercury	4.55	18	18	90,584.3	18,241.7	0.8625	15,733.4	283,201.6	0.0	351,000.0	724,785.9	22.6
N_2H_4/Mercury	4.18	20	20	94,495.7	18,528.5	0.8565	15,869.7	317,393.3	0.0	390,000.0	801,889.0	14.4
Ablative Teflon	2.91	26	26	88,467.8	17,935.2	0.8416	15,094.3	392,451.2	0.0	507,000.0	987,919.0	-5.5
N_2H_4/Teflon	3.22	24	24	88,100.0	16,531.0	0.8461	13,986.9	335,684.7	0.0	468,000.0	891,784.7	4.8
MPD	3.20	24	24	88,056.7	17,803.2	0.8461	15,063.3	361,519.3	0.0	468,000.0	917,576.0	2.0
N_2H_4/MPD	3.49	23	23	93,484.1	18,408.6	0.8486	15,621.5	359,295.1	0.0	448,500.0	901,279.2	3.8

TABLE D10

COST OF TWELVE MEDIUM CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

II. Enhancement of MMD without Weight Penalty (all satellites weigh 2,000 pounds)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost	Percent Improvement
Mono. Hydrazine	3.00	50	50	72,896.1	17,824.5	0.8045	14,339.8	716,990.5	0.0	975,000.0	1,764,886.6	0.0
N_2H_4/Resistojet	3.07	49	49	73,257.5	17,927.6	0.8056	14,442.5	707,681.3	0.0	955,500.0	1,736,438.8	1.6
Cesium	3.60	44	44	89,421.2	18,015.5	0.8117	14,623.2	643,420.0	0.0	858,000.0	1,590,841.2	9.9
N_2H_4/Cesium	3.70	43	43	94,222.8	18,520.2	0.8130	15,056.9	647,447.7	0.0	838,500.0	1,580,170.5	10.5
Colloid	4.26	38	38	89,163.8	17,817.7	0.8200	14,610.5	555,199.5	0.0	741,000.0	1,385,363.3	21.5
N_2H_4/Colloid	4.06	40	40	93,731.2	18,262.7	0.8171	14,922.5	596,898.1	0.0	780,000.0	1,470,629.3	16.7
Mercury	4.55	36	36	90,584.3	18,241.7	0.8231	15,014.7	540,530.8	0.0	702,000.0	1,333,115.1	24.5
N_2H_4/Mercury	4.18	39	39	94,495.7	18,528.5	0.8185	15,165.6	591,457.5	0.0	760,500.0	1,446,453.2	18.0
Ablative Teflon	2.91	51	51	88,467.8	17,935.2	0.8034	14,409.1	734,866.1	0.0	994,500.0	1,817,833.9	-3.0
N_2H_4/Teflon	3.22	48	48	88,100.0	16,531.0	0.8068	13,337.2	640,186.1	0.0	936,000.0	1,664,286.1	5.7
MPD	3.20	48	48	88,056.7	17,803.2	0.8068	14,363.6	689,453.8	0.0	936,000.0	1,713,510.5	2.9
N_2H_4/MPD	3.49	45	45	93,484.1	18,408.6	0.8104	14,918.3	671,324.8	0.0	877,500.0	1,642,308.9	6.9

TABLE [illegible]

COST OF SIX LARGE CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

II. Enhancement of MMD without Weight Penalty (all satellites weigh 3,000 pounds)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost	Percent Improvement
Mono. Hydrazine	3.00	25	25	85,637.8	21,522.1	0.8438	18,160.3	454,008.7	0.0	487,500.0	1,027,146.5	0.0
N_2H_4/Resistojet	3.03	25	25	86,249.0	21,747.3	0.8438	18,350.4	458,760.0	0.0	487,500.0	1,032,509.0	-0.5
Cesium	3.64	22	22	103,042.4	21,722.1	0.8511	18,487.7	406,729.3	0.0	429,000.0	938,771.7	8.6
N_2H_4/Cesium	3.60	22	22	107,720.2	22,267.2	0.8511	18,951.6	416,934.8	0.0	429,000.0	953,655.0	7.2
Colloid	4.13	20	20	102,138.5	21,343.6	0.8565	18,280.8	365,615.3	0.0	400,000.0	867,753.8	15.5
N_2H_4/Colloid	3.96	20	20	106,871.1	21,875.3	0.8565	18,736.2	374,723.5	0.0	400,000.0	881,594.6	14.2
Mercury	4.20	19	19	103,196.2	21,708.6	0.8594	18,656.4	354,471.4	0.0	370,500.0	828,167.6	19.4
N_2H_4/Mercury	4.00	20	20	107,525.6	22,095.7	0.8565	18,925.0	378,499.3	0.0	400,000.0	886,024.9	13.7
Ablative Teflon	3.07	25	25	101,362.5	21,389.7	0.8438	18,048.7	451,216.6	0.0	487,500.0	1,040,079.1	-1.3
N_2H_4/Teflon	3.18	24	24	107,056.3	22,204.5	0.8461	18,787.3	450,894.2	0.0	468,000.0	1,025,950.5	0.1
MPD	3.32	23	23	101,703.6	21,544.5	0.8486	18,282.6	420,500.9	0.0	448,500.0	970,704.5	5.5
N_2H_4/MPD	3.40	23	23	106,741.8	22,111.6	0.8486	18,763.9	431,569.4	6,000.0	452,500.0	996,811.2	3.0

TABLE D12

COST OF TWELVE LARGE CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

II. Enhancement of MMD without Weight Penalty (all satellites weigh 3,000 pounds)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost	Percent Improvement
Mono. Hydrazine	3.00	50	50	85,637.8	21,522.1	0.8045	17,314.5	865,726.5	0.0	975,000.0	1,926,364.3	0.0
N_2H_4/Resistojet	3.03	50	50	86,249.0	21,747.3	0.8045	17,495.7	874,785.1	0.0	975,000.0	1,936,034.1	-0.5
Cesium	3.64	44	44	103,042.4	21,722.1	0.8117	17,631.8	775,800.5	0.0	858,000.0	1,736,842.9	9.8
N_2H_4/Cesium	3.60	44	44	107,720.2	22,267.2	0.8117	18,074.3	795,268.6	0.0	858,000.0	1,760,988.8	8.6
Colloid	4.13	40	40	102,138.5	21,343.6	0.8171	17,439.9	697,594.2	0.0	800,000.0	1,599,732.7	17.0
N_2H_4/Colloid	3.96	40	40	106,871.1	21,875.3	0.8171	17,874.3	714,972.3	0.0	800,000.0	1,621,843.4	15.8
Mercury	4.20	38	38	103,196.2	21,708.6	0.8200	17,801.1	676,440.0	0.0	741,000.0	1,520,636.2	21.1
N_2H_4/Mercury	4.00	40	40	107,525.6	22,095.7	0.8171	18,054.4	722,175.9	0.0	800,000.0	1,629,701.5	15.4
Ablative Teflon	3.07	50	50	101,362.5	21,389.7	0.8045	17,208.0	860,400.7	0.0	975,000.0	1,936,763.2	-0.5
N_2H_4/Teflon	3.18	48	48	107,056.3	22,204.5	0.8068	17,914.6	859,900.4	0.0	936,000.0	1,902,956.7	1.2
MPD	3.32	46	46	101,703.6	21,544.5	0.8092	17,433.8	801,955.2	0.0	897,000.0	1,800,658.8	6.5
N_2H_4/MPD	3.40	46	46	106,741.8	22,111.6	0.8092	17,892.7	823,064.5	6,000.0	897,000.0	1,832,806.3	4.9

TABLE D13

COST OF CONSTELLATION OF SIX SMALL CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

III. Cost of Satellites with Monopropellant Hydrazine Compared with the Cost of 7-Year Satellites with Electric Propulsion

(Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost	Percent Improvement
N_2H_4/Resistojet	7.00	13	6.5	64,853.1	14,523.2	0.8808	12,792.0	166,296.0	0.0	126,750.0	357,899.1	0.2
Mono Hydrazine	6.65	13	6.5	64,902.8	14,587.1	0.8808	12,848.3	167,028.0	0.0	126,750.0	358,680.8	
Cesium	7.00	13	6.5	78,803.6	14,046.3	0.8808	12,372.0	160,836.0	0.0	126,750.0	366,389.6	10.5
Mono. Hydrazine	5.26	16	8.0	62,066.4	13,672.8	0.8692	11,884.4	190,150.6	0.0	156,000.0	408,217.0	
N_2H_4/Cesium	7.00	13	6.5	82,782.3	14,333.5	0.8808	12,624.9	164,123.7	0.0	126,750.0	373,656.0	12.0
Mono. Hydrazine	4.90	17	8.5	61,248.5	13,409.8	0.8657	11,608.8	197,350.2	0.0	165,750.0	424,348.5	
Colloid	7.00	13	6.5	76,225.7	13,272.3	0.8808	11,690.2	151,972.6	0.0	126,750.0	354,948.3	16.2
Mono. Hydrazine	4.84	17	8.5	61,075.8	13,354.6	0.8657	11,561.0	196,537.6	0.0	165,750.0	423,363.4	
N_2H_4/Colloid	7.00	13	6.5	81,572.1	13,912.8	0.8808	12,254.4	159,307.2	0.0	126,750.0	367,629.3	13.5
Mono. Hydrazine	4.93	17	8.5	61,334.6	13,437.4	0.8657	11,632.7	197,756.6	0.0	165,750.0	424,841.2	
Mercury	7.00	13	6.5	76,845.8	13,483.6	0.8808	11,876.4	154,399.2	0.0	126,750.0	357,995.0	18.3
Mono. Hydrazine	4.49	18	9.0	60,069.7	13,032.5	0.8625	11,240.5	202,328.7	0.0	175,500.0	437,898.4	
N_2H_4/Mercury	7.00	13	6.5	81,559.2	13,965.6	0.8808	12,300.9	159,911.7	0.0	126,750.0	368,220.9	16.0
Mono. Hydrazine	4.50	18	9.0	60,098.4	13,041.7	0.8625	11,248.4	202,471.6	0.0	175,500.0	438,070.0	
Ablative Teflon	7.00	13	6.5	79,708.7	14,309.6	0.8808	12,603.9	163,850.7	0.0	126,750.0	370,309.4	5.2
Mono. Hydrazine	5.56	15	7.5	62,678.5	13,870.1	0.8728	12,105.8	181,587.9	0.0	146,250.0	390,516.4	
N_2H_4/Teflon	7.00	13	6.5	83,173.7	14,455.5	0.8808	12,732.4	165,521.2	0.0	126,750.0	375,444.9	4.6
Mono. Hydrazine	5.84	15	7.5	63,249.4	14,054.3	0.8728	12,266.6	183,998.9	0.0	146,250.0	393,498.3	
MPD	7.00	13	6.5	79,140.3	14,231.3	0.8808	12,534.9	162,953.7	0.0	126,750.0	368,344.0	6.2
Mono. Hydrazine	5.81	15	7.5	63,188.7	14,034.6	0.8728	12,249.4	183,740.7	0.0	146,250.0	393,179.4	
N_2H_4/MPD	7.00	13	6.5	83,013.7	14,457.0	0.8088	12,733.7	165,538.1	0.0	126,750.0	375,301.8	7.9
Mono. Hydrazine	5.18	16	8.0	61,903.1	13,620.2	0.8692	11,838.7	189,418.8	0.0	156,000.0	407,321.9	

TABLE D14

COST OF CONSTELLATION OF TWELVE SMALL CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

III. Cost of Satellites with Monopropellant Hydrazine Compared with the Cost of 7-Year Satellites with Electric Propulsion

(Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost	Percent Improvement
N_2H_4/Resistojet	7.00	26	13	64,853.1	14,523.2	0.8416	12,222.7	317,790.2	0.0	253,500.0	636,143.3	0.2
Mono. Hydrazine	6.65	26	13	64,902.8	14,587.1	0.8416	12,276.5	319,189.1	0.0	253,500.0	637,591.9	
Cesium	7.00	26	13	78,803.6	14,046.3	0.8416	11,821.4	307,356.4	0.0	253,500.0	639,660.0	13.2
Mono. Hydrazine	5.26	32	16	62,066.4	13,672.8	0.8298	11,345.7	363,062.1	0.0	312,000.0	737,128.5	
N_2H_4/Cesium	7.00	26	13	82,782.3	14,333.5	0.8416	12,063.1	313,640.6	0.0	253,500.0	649,922.9	15.5
Mono. Hydrazine	4.90	34	17	61,248.3	13,409.8	0.8263	11,080.5	376,737.6	0.0	331,500.0	769,485.9	
Colloid	7.00	26	13	76,225.7	13,272.3	0.8416	11,170.0	290,420.0	0.0	253,500.0	620,145.7	19.2
Mono. Hydrazine	4.84	34	17	61,075.8	13,354.6	0.8263	11,034.9	375,186.8	0.0	331,500.0	767,762.6	
N_2H_4/Colloid	7.00	26	13	81,572.1	13,912.8	0.8416	11,709.0	304,434.0	0.0	253,500.0	639,506.1	17.0
Mono. Hydrazine	4.93	34	17	61,334.6	13,437.4	0.8263	11,103.3	377,513.0	0.0	331,500.0	770,347.6	
Mercury	7.00	26	13	76,845.8	13,483.6	0.8416	11,347.8	295,042.8	0.0	253,500.0	625,388.6	21.6
Mono. Hydrazine	4.49	36	18	60,069.7	13,032.5	0.8231	10,727.1	386,173.8	0.0	351,000.0	797,243.5	
N_2H_4/Mercury	7.00	26	13	81,559.2	13,965.6	0.8416	11,753.5	305,591.0	0.0	253,500.0	640,650.2	19.7
Mono. Hydrazine	4.50	36	18	60,098.4	13,041.7	0.8231	10,734.6	386,446.4	0.0	351,000.0	797,544.8	
Ablative Teflon	7.00	26	13	79,708.7	14,309.6	0.8416	12,043.0	313,116.9	0.0	253,500.0	646,325.6	7.9
Mono. Hydrazine	5.56	30	15	62,678.5	13,870.1	0.8334	11,559.3	346,780.2	0.0	292,500.0	7[illegible]1,958.7	
N_2H_4/Teflon	7.00	26	13	83,173.7	14,455.5	0.8416	12,165.8	316,309.5	0.0	253,500.0	652,983.2	7.7
Mono. Hydrazine	5.84	30	15	63,249.4	14,054.3	0.8334	11,712.9	351,385.6	0.0	292,500.0	707,135.0	
MPD	7.00	26	13	79,140.3	14,231.3	0.8416	11,977.1	311,403.6	0.0	253,500.0	644,043.9	8.9
Mono. Hydrazine	5.81	30	15	63,188.7	14,034.6	0.8334	11,696.4	350,893.1	0.0	292,500.0	706,581.8	
N_2H_4/MPD	7.00	26	13	83,013.7	14,457.0	0.8416	12,167.0	316,342.3	0.0	253,500.0	652,856.0	11.3
Mono. Hydrazine	5.18	32	16	61,903.1	13,620.2	0.8298	11,302.0	361,665.3	0.0	312,000.0	735,568.4	

TABLE D15

COST OF CONSTELLATION OF SIX MEDIUM CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

III Cost of Satellites with Monopropellant Hydrazine Compared with the Cost of 7-Year Satellites with Electric Propulsion

(Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost	Percent Improvement
N_2H_4/Resistojet	7.00	13	13	87,203.5	22,119.5	0.8808	19,482.9	253,277.1	0.0	253,500.0	593,980.6	-0.3
Mono. Hydrazine	6.90	13	13	86,854.1	22,001.9	0.8808	19,379.2	251,930.1	0.0	253,500.0	592,284.2	
Cesium	7.00	13	13	99,882.0	20,909.5	0.8808	18,417.1	239,422.1	0.0	253,500.0	592,804.1	12.3
Mono. Hydrazine	5.11	16	16	81,525.0	20,297.1	0.8692	17,642.2	282,275.2	0.0	312,000.0	675,800.2	
N_2H_4/Cesium	7.00	13	13	104,689.3	21,495.1	0.8808	18,932.9	246,127.5	0.0	253,500.0	504,316.8	10.5
Mono. Hydrazine	5.09	16	16	81,465.4	20,278.0	0.8692	17,625.7	282,010.4	0.0	312,000.0	675,475.8	
Colloid	7.00	13	13	96,995.6	19,974.6	0.8808	17,593.6	228,717.2	0.0	253,500.0	579,212.8	21.2
Mono. Hydrazine	4.58	18	18	79,424.3	19,630.9	0.8625	16,931.6	304,769.5	0.0	351,000.0	735,193.8	
N_2H_4/Colloid	7.00	13	13	102,760.5	20,818.6	0.8808	18,337.0	238,381.2	0.0	253,500.0	594,641.8	12.1
Mono. Hydrazine	5.16	16	16	81,673.8	20,344.7	0.8692	17,683.6	282,937.6	0.0	312,000.0	676,611.4	
Mercury	7.00	13	13	97,092.0	20,074.6	0.8808	17,631.7	229,862.2	0.0	253,500.0	580,454.2	24.1
Mono. Hydrazine	4.38	19	19	78,579.9	19,363.5	0.8594	16,641.0	316,179.6	0.0	370,500.0	765,259.5	
N_2H_4/Mercury	7.00	13	13	102,805.4	20,930.7	0.8808	18,435.8	239,664.9	0.0	253,500.0	595,970.3	15.3
Mono. Hydrazine	4.74	17	17	80,099.8	19,844.8	0.8657	17,179.6	292,053.3	0.0	311,500.0	703,653.1	
Ablative Teflon	7.00	13	13	101,800.4	21,553.4	0.8808	18,984.2	246,795.1	0.0	253,500.0	602,095.5	7.1
Mono. Hydrazine	5.64	15	15	83,102.9	20,801.8	0.8728	18,155.8	272,337.6	0.0	292,500.0	647,940.5	
N_2H_4/Teflon	7.00	13	13	100,573.8	19,994.5	0.8808	17,611.2	228,945.0	0.0	253,500.0	583,018.8	10.0
Mono. Hydrazine	5.62	15	15	83,043.3	20,782.8	0.8728	18,139.2	272,088.3	0.0	292,500.0	647,631.6	
MPD	7.00	13	13	100,270.8	21,155.5	0.8808	18,633.8	242,238.9	0.0	253,500.0	596,009.9	7.8
Mono. Hydrazine	5.54	15	15	82,805.2	20,706.6	0.8728	18,072.7	271,090.8	0.0	292,500.0	646,396.0	
N_2H_4/MPD	7.00	13	13	104,892.8	21,629.5	0.8808	19,051.3	247,666.4	0.0	253,500.0	606,059.2	10.8
Mono. Hydrazine	5.34	16	16	82,209.7	20,516.1	0.8692	17,832.6	285,321.5	0.0	312,000.0	679,531.2	

TABLE D16

COST OF CONSTELLATION OF TWELVE MEDIUM CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

III. Cost of Satellites with Monopropellant Hydrazine Compared with the Cost of 7-Year Satellites with Electric Propulsion

(Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost	Percent Improvement
N_2H_4/Resistojet	7.00	26	26	87,203.5	22,119.5	0.8416	18,615.8	484,010.1	0.0	507,000.0	1,078,213.6	-0.3
Mono. Hydrazine	6.90	26	26	86,854.1	22,001.9	0.8416	18,516.8	481,436.8	0.0	507,000.0	1,075,290.9	
Cesium	7.00	26	26	99,882.0	20,909.5	0.8416	17,597.4	457,533.3	0.0	507,000.0	1,064,415.3	14.5
Mono. Hydrazine	5.11	32	32	81,525.0	20,297.1	0.8298	16,842.5	538,961.1	0.0	624,000.0	1,244,486.1	
N_2H_4/Cesium	7.00	26	26	104,689.3	21,495.1	0.8416	18,090.3	470,347.2	0.0	507,000.0	1,082,036.5	13.0
Mono. Hydrazine	5.09	32	32	81,465.4	20,278.0	0.8298	16,826.7	538,453.9	0.0	624,000.0	1,243,919.3	
Colloid	7.00	26	26	96,995.6	19,974.6	0.8416	16,810.6	437,076.2	0.0	507,000.0	1,041,071.8	23.6
Mono. Hydrazine	4.58	36	36	79,424.3	19,630.9	0.8231	16,158.2	581,695.0	0.0	702,000.0	1,363,119.3	
N_2H_4/Colloid	7.00	26	26	102,760.5	20,818.6	0.8416	17,520.9	455,544.3	0.0	507,000.0	1,065,304.8	14.5
Mono. Hydrazine	5.16	32	32	81,673.8	20,344.7	0.8298	16,882.0	540,225.0	0.0	624,000.0	1,245,898.8	
Mercury	7.00	26	26	97,092.0	20,074.6	0.8416	16,894.8	439,264.4	0.0	507,000.0	1,043,356.4	26.7
Mono. Hydrazine	4.38	38	38	78,579.9	19,363.5	0.8200	15,878.1	603,366.7	0.0	741,000.0	1,422,946.6	
N_2H_4/Mercury	7.00	26	26	102,805.4	20,930.7	0.8416	17,615.3	457,997.2	0.0	507,000.0	1,067,802.6	17.9
Mono. Hydrazine	4.74	34	34	80,099.8	19,844.8	0.8263	16,397.8	557,523.8	0.0	663,000.0	1,300,623.6	
Ablative Teflon	7.00	26	26	101,800.4	21,553.4	0.8416	18,139.3	471,622.9	0.0	507,000.0	1,080,423.3	14.2
Mono. Hydrazine	5.64	32	32	83,102.9	20,801.8	0.8298	17,261.3	552,362.7	0.0	624,000.0	1,259,465.6	
N_2H_4/Teflon	7.00	26	26	100,573.8	19,994.5	0.8416	16,827.4	437,511.7	0.0	507,000.0	1,045,085.5	12.0
Mono. Hydrazine	5.62	30	30	83,043.3	20,782.8	0.8334	17,320.4	519,611.6	0.0	585,000.0	1,187,654.9	
MPD	7.00	26	26	100,270.8	21,155.5	0.8416	17,804.5	462,916.2	0.0	507,000.0	1,070,187.0	9.7
Mono. Hydrazine	5.54	30	30	82,805.2	20,706.6	0.8334	17,256.9	517,706.4	0.0	585,000.0	1,185,511.6	
N_2H_4/MPD	7.00	26	26	104,892.8	21,629.5	0.8416	18,203.4	473,288.1	0.0	507,000.0	1,085,180.9	13.3
Mono. Hydrazine	5.34	32	32	82,209.7	20,516.1	0.8298	17,024.3	544,776.3	0.0	624,000.0	1,250,986.0	

TABLE D17

COST OF CONSTELLATION OF SIX LARGE CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

III. Cost of Satellites with Monopropellant Hydrazine Compared with the Cost of 7-Year Satellites with Electric Propulsion

(Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MMD (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost	Percent Improvement
N_2H_4/Resistojet	7.00	13	13	104,193.2	27,330.5	0.8808	24,072.7	312,945.2	10,000.0	273,000.0	700,138.4	-0.6
Mono. Hydrazine	6.97	13	13	103,482.5	27,049.2	0.8808	23,824.9	309,723.6	10,000.0	273,000.0	696,206.1	
Cesium	7.00	13	13	115,886.8	25,480.2	0.8808	22,443.0	291,759.0	9,500.0	260,000.0	677,145.8	16.2
Mono. Hydrazine	5.00	17	17	96,129.5	24,596.6	0.8657	21,293.3	361,985.7	9,500.0	340,000.0	807,615.2	
N_2H_4/Cesium	7.00	13	13	121,311.5	26,299.7	0.8808	23,164.8	301,142.1	6,000.0	260,000.0	688,453.6	14.2
Mono. Hydrazine	5.17	16	16	102,960.0	26,874.9	0.8692	23,359.6	373,754.0	9,500.0	320,000.0	806,214.0	
Colloid	7.00	13	13	112,550.9	24,386.7	0.8808	21,479.8	279,237.5	6,000.0	260,000.0	657,788.4	17.5
Mono. Hydrazine	4.78	17	17	94,959.9	24,210.0	0.8657	20,958.6	356,295.7	6,000.0	340,000.0	797,255.6	
N_2H_4/Colloid	7.00	13	13	118,605.0	25,363.1	0.8808	22,339.8	290,417.6	6,000.0	260,000.0	675,022.6	15.8
Mono. Hydrazine	4.93	17	17	95,757.3	24,473.6	0.8657	21,186.8	360,175.3	6,000.0	340,000.0	801,932.6	
Mercury	7.00	13	13	112,953.1	24,651.2	0.8808	21,712.8	282,266.1	6,000.0	260,000.0	661,219.2	20.4
Mono. Hydrazine	4.59	18	18	93,949.7	23,876.1	0.8625	20,593.1	370,675.9	6,000.0	360,000.0	830,625.6	
N_2H_4/Mercury	7.00	13	13	118,732.7	25,526.3	0.8808	22,483.6	292,286.4	6,000.0	260,000.0	677,019.1	15.2
Mono. Hydrazine	4.83	17	17	95,225.7	24,297.8	0.8657	21,034.6	357,588.9	6,000.0	340,000.0	798,814.6	
Ablative Teflon	7.00	13	13	118,218.8	26,273.1	0.8808	23,141.4	300,837.5	9,500.0	260,000.0	688,556.3	7.1
Mono. Hydrazine	5.67	15	15	98,630.3	25,430.7	0.8728	22,195.9	332,938.9	9,500.0	300,000.0	741,069.2	
N_2H_4/Teflon	7.00	13	13	122,753.4	26,769.1	0.8808	23,578.2	306,516.9	9,500.0	260,000.0	698,770.3	5.8
Mono. Hydrazine	5.69	15	15	98,704.9	25,455.6	0.8728	22,217.7	333,264.9	9,500.0	300,000.0	741,469.8	
MPD	7.00	13	13	116,312.9	25,789.6	0.8808	22,715.5	295,301.2	9,500.0	260,000.0	681,114.1	12.2
Mono. Hydrazine	5.36	16	16	97,473.2	25,044.8	0.8692	21,768.9	348,302.8	9,500.0	320,000.0	775,276.0	
N_2H_4/MPD	7.00	13	13	121,453.2	26,448.7	0.8808	23,296.0	302,848.2	9,500.0	260,000.0	693,801.4	10.6
Mono. Hydrazine	5.38	16	16	97,547.9	25,069.7	0.8692	21,790.6	348,649.1	9,500.0	320,000.0	775,697.0	

TABLE D18

COST OF CONSTELLATION OF TWELVE LARGE CATEGORY SATELLITES IN ORBIT FOR TEN YEARS

III. Cost of Satellites with Monopropellant Hydrazine Compared with the Cost of 7-Year Satellites with Electric Propulsion

(Costs in thousands of 1973 dollars)

Type of Propulsion Subsystem	MML (Years)	No. of Satellites	No. of LVs	Satellite Nonrecurring Cost	First Unit Cost	Satellite Recurring Cost: Learning Curve Factor	Satellite Recurring Cost: Cumulative Avg. Cost	Satellite Recurring Cost: Total Recurring Sat. Cost	Launch Vehicle Cost: Nonrecurring Cost	Launch Vehicle Cost: Recurring Cost	Total System Cost	Percent Improvement
N_2H_4/Resistojet	7.00	26	26	104,193.2	27,330.5	0.8416	22,796.0	592,696.0	10,000.0	546,000.0	1,258,228.3	-0.6
Mono. Hydrazine	6.97	26	26	103,482.5	27,049.2	0.8416	22,764.6	591,879.8	10,000.0	546,000.0	1,251,362.3	
Cesium	7.00	26	26	115,886.8	25,480.2	0.8416	23,001.3	598,035.1	9,500.0	520,000.0	1,202,934.3	18.5
Mono. Hydrazine	5.00	34	34	96,129.5	24,596.6	0.8263	20,324.2	691.021.8	9,500.0	680,000.0	1,476,651.3	
N_2H_4/Cesium	7.00	26	26	121,311.5	26,299.7	0.8416	22,133.8	575,479.5	6,000.0	520,000.0	1,222,791.0	16.6
Mono. Hydrazine	5.17	32	32	102,960.0	26,874.9	0.8298	22,300.8	713,625.3	9,500.0	640,000.0	1,466,085.3	
Colloid	7.00	26	26	112,550.9	24,386.7	0.8416	20,523.8	533,620.0	6,000.0	520,000.0	1,172,170.9	19.8
Mono. Hydrazine	4.78	34	34	94,959.9	24,210.0	0.8263	20,004.7	680,160.6	6,000.0	680,000.0	1,461,120.5	
N_2H_4/Colloid	7.00	26	26	118,605.0	25,363.1	0.8416	21,345.6	554,985.2	6,000.0	520,000.0	1,119,590.2	18.4
Mono. Hydrazine	4.93	34	34	95,757.3	24,473.6	0.3263	20,222.5	687,566.2	6,000.0	680,000.0	1,469,323.5	
Mercury	7.00	26	26	112,953.1	24,651.2	0.8416	20,746.5	539.407.7	6,000.0	520,000.0	1,178,360.8	22.9
Mono. Hydrazine	4.59	36	36	93,949.7	23,876.1	0.8231	19,652.4	707,487.0	6,000.0	720,000.0	1,527,436.7	
N_2H_4/Mercury	7.00	26	26	118,732.7	25,526.3	0.8416	21,482.9	558,556.3	6,000.0	520,000.0	1,203,289.0	17.8
Mono. Hydrazine	4.83	34	34	95,225.7	24,297.8	0.8263	20,077.3	682,627.3	6,000.0	680,000.0	1,463,853.0	
Ablative Teflon	7.00	26	26	118,218.8	26,273.1	0.8416	22,111.4	574,897.5	9,500.0	520,000.0	1,222,616.3	9.0
Mono. Hydrazine	5.67	30	30	98,630.3	25,430.7	0.8334	21,193.9	635,818.4	9,500.0	600,000.0	1,343,948.7	
N_2H_4/Teflon	7.00	26	26	122,753.4	26,769.1	0.8416	22,528.9	585,750.7	9,500.0	520,000.0	1,238,004.1	7.9
Mono. Hydrazine	5.69	30	30	98,704.9	25,455.6	0.8334	21,214.7	636,440.9	9,500.0	600,000.0	1,344,645.8	
MPD	7.00	26	26	116,312.9	25,789.6	0.8416	21,704.5	564,317.7	9,500.0	520,000.0	1,210,130.6	14.3
Mono. Hydrazine	5.36	32	26	97,473.2	25,044.8	0.8298	20,782.2	665,029.6	9,500.0	640,000.0	1,412,002.8	
N_2H_4/MPD	7.00	26	26	121,453.2	26,448.7	0.8416	22,259.2	578,739.9	9,500.0	520,000.0	1,229,693.1	13.0
Mono. Hydrazine	5.38	32	32	97,547.9	25,069.7	0.8298	20,802.8	665,690.8	9,500.0	640,000.0	1,412,738.7	

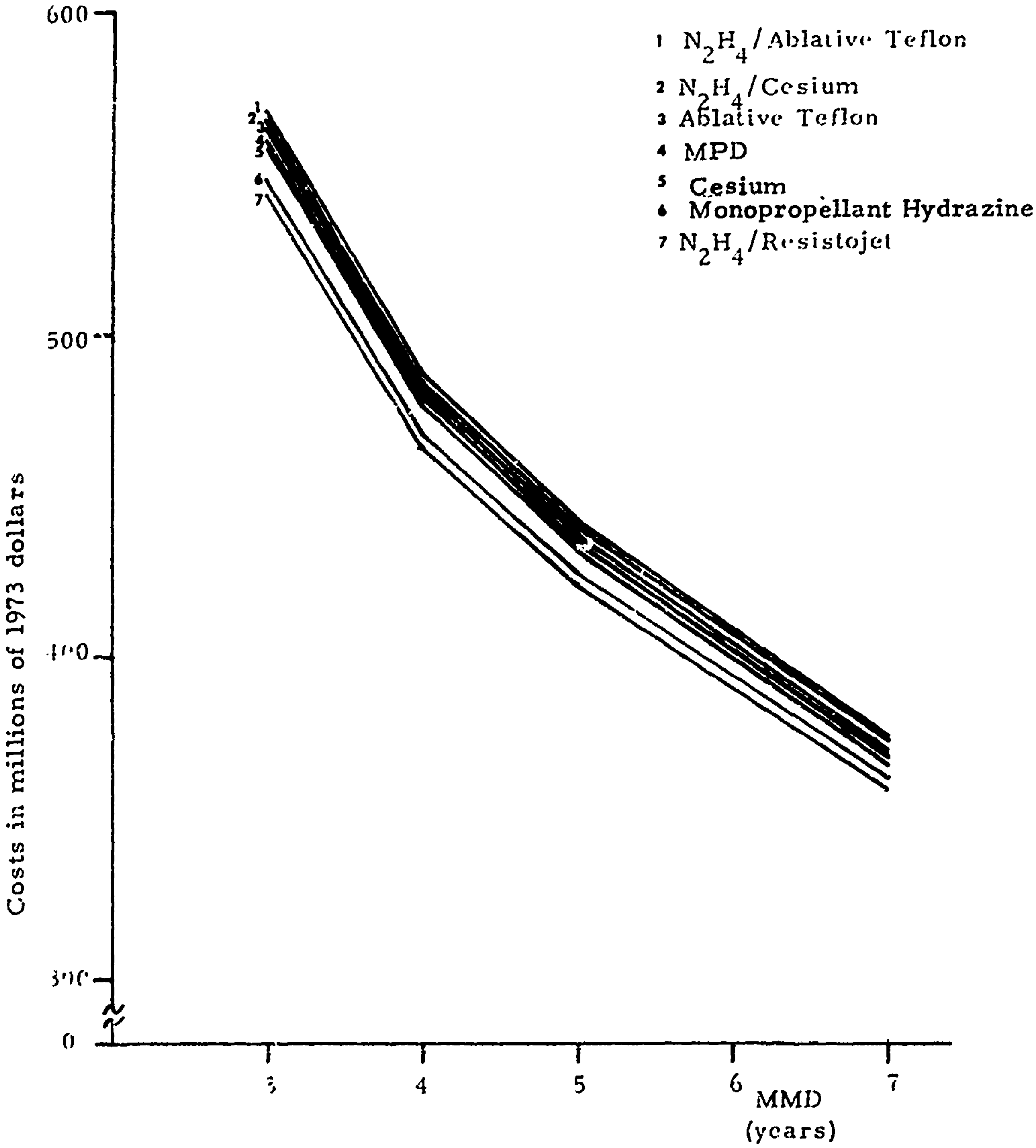


Fig. D1 Ten-Year System Cost of Constellation of Six Small Category Satellites as a Function of the Mean Mission of the Satellite

(continued)

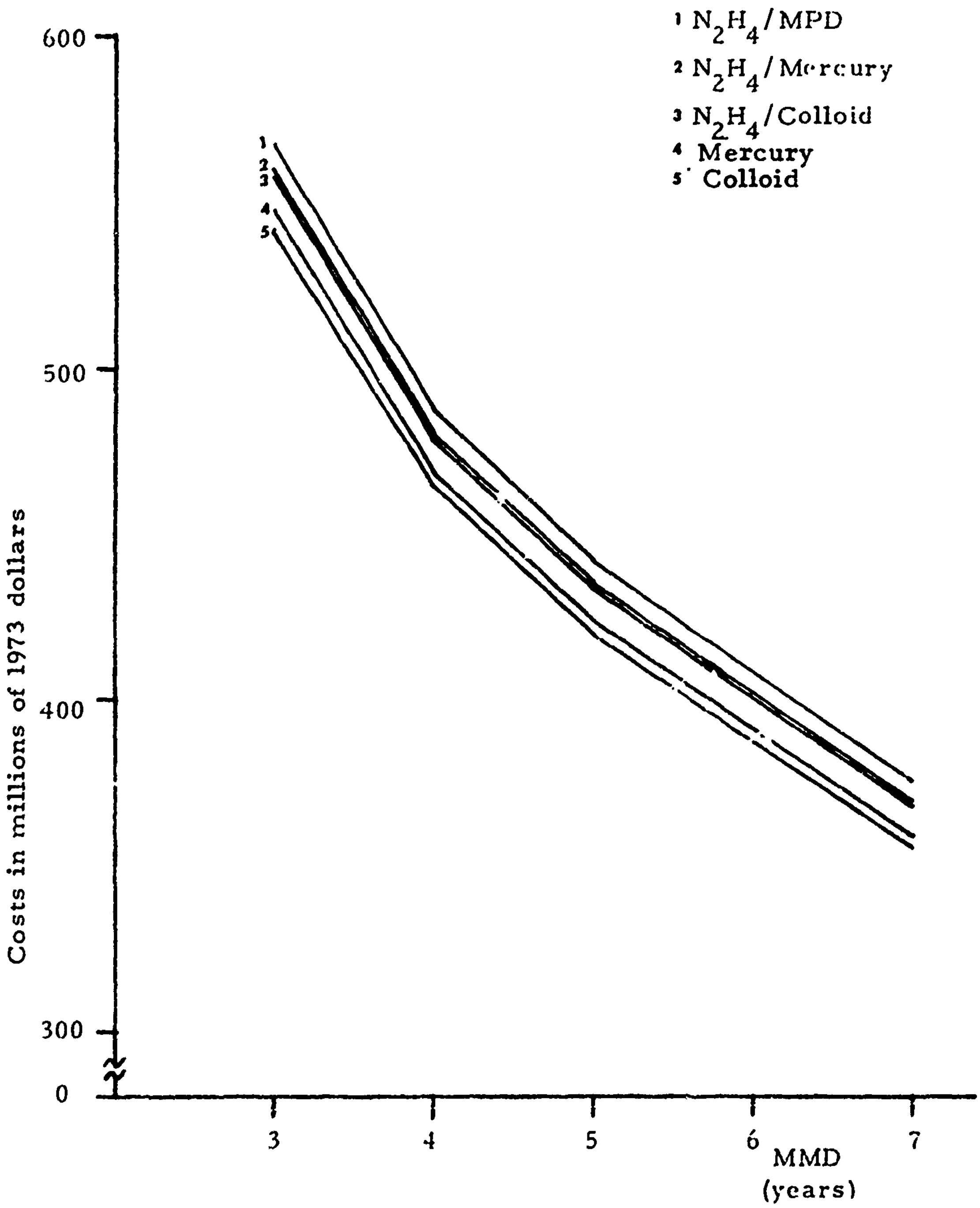


Fig. D1 (continued)

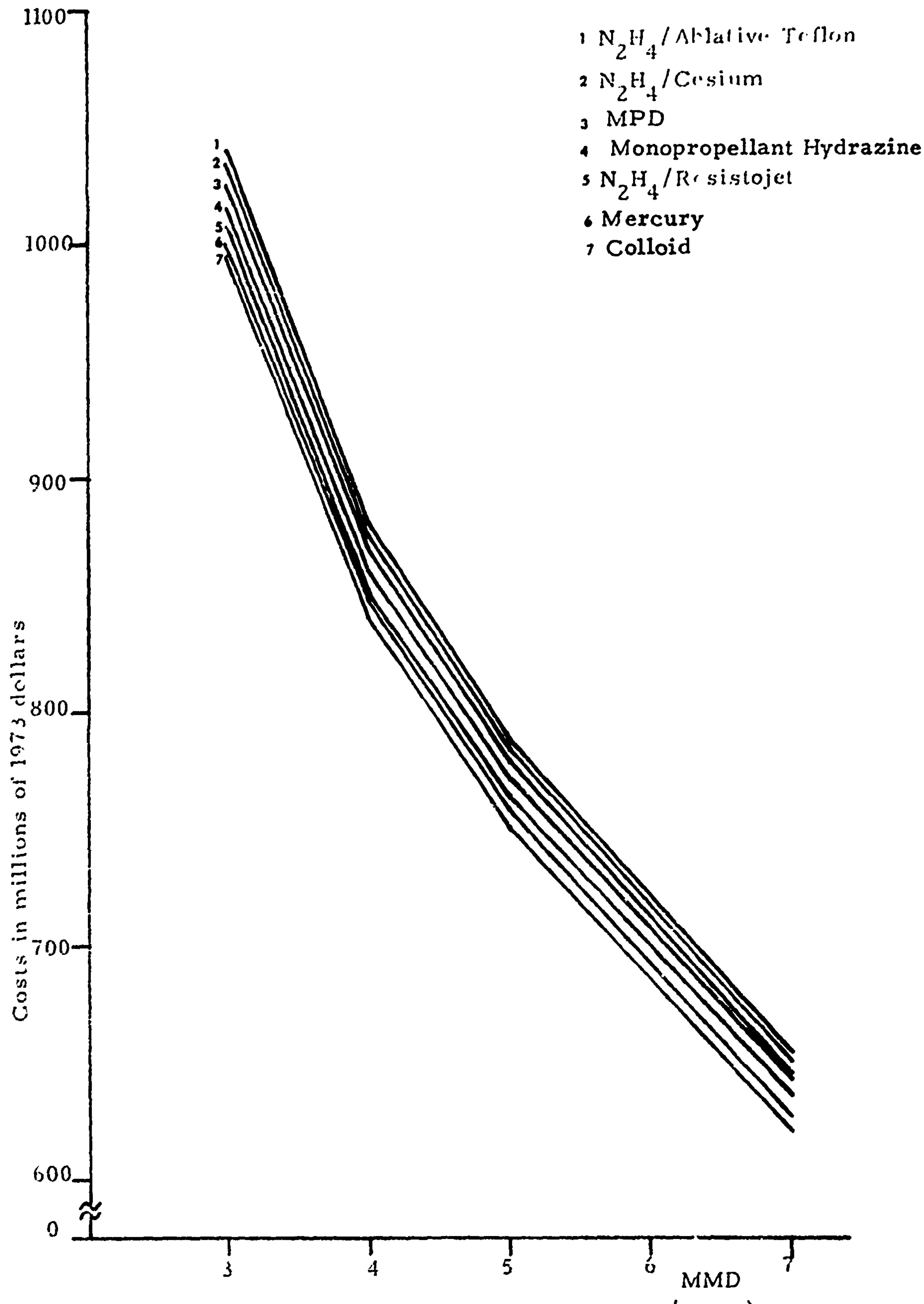


Fig. D2 Ten-Year System Cost of Constellation of Twelve Small Category Satellites as a Function of the Mean Mission of the Satellite

(continued)

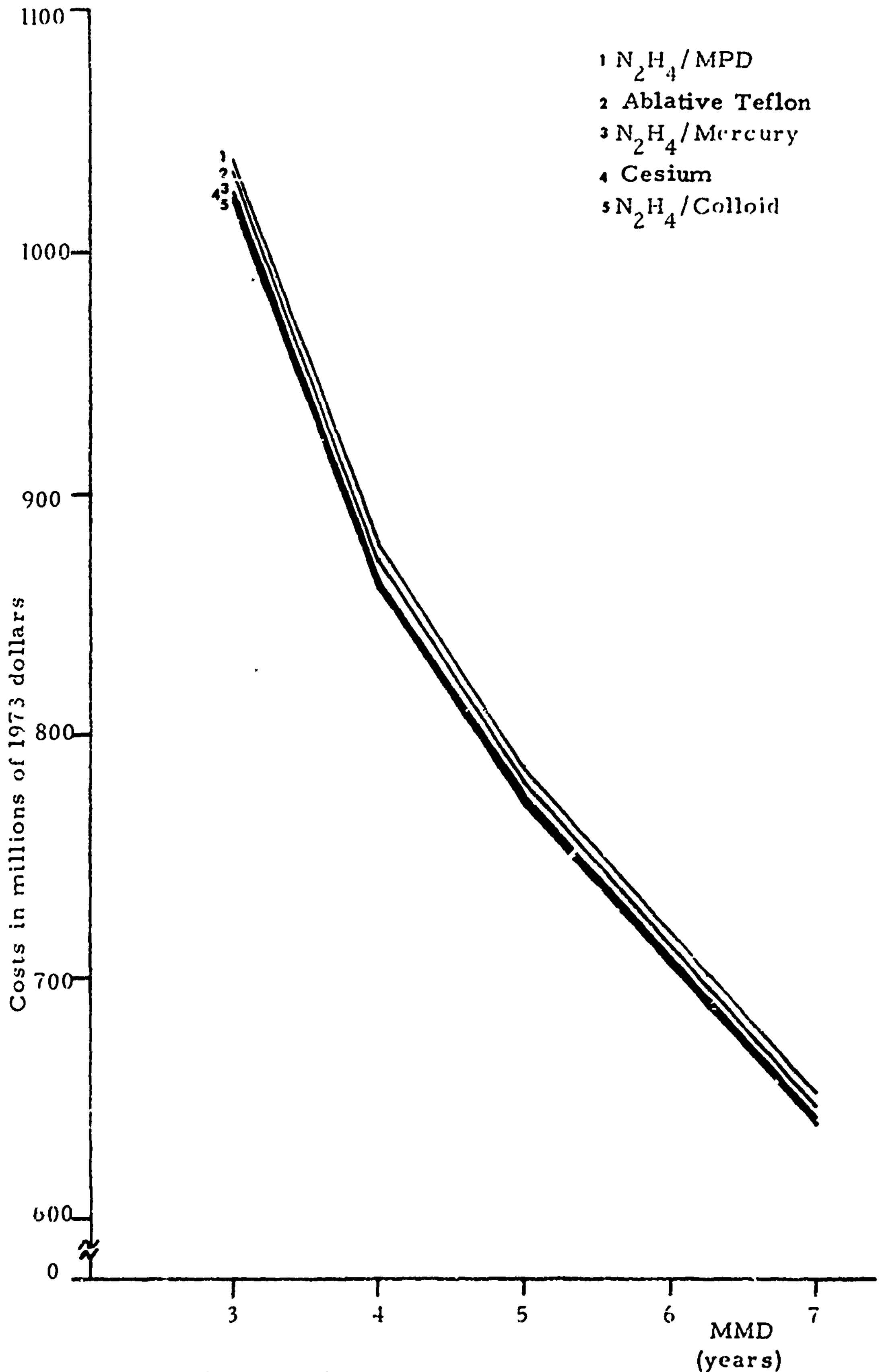


Fig. D2 (continued)

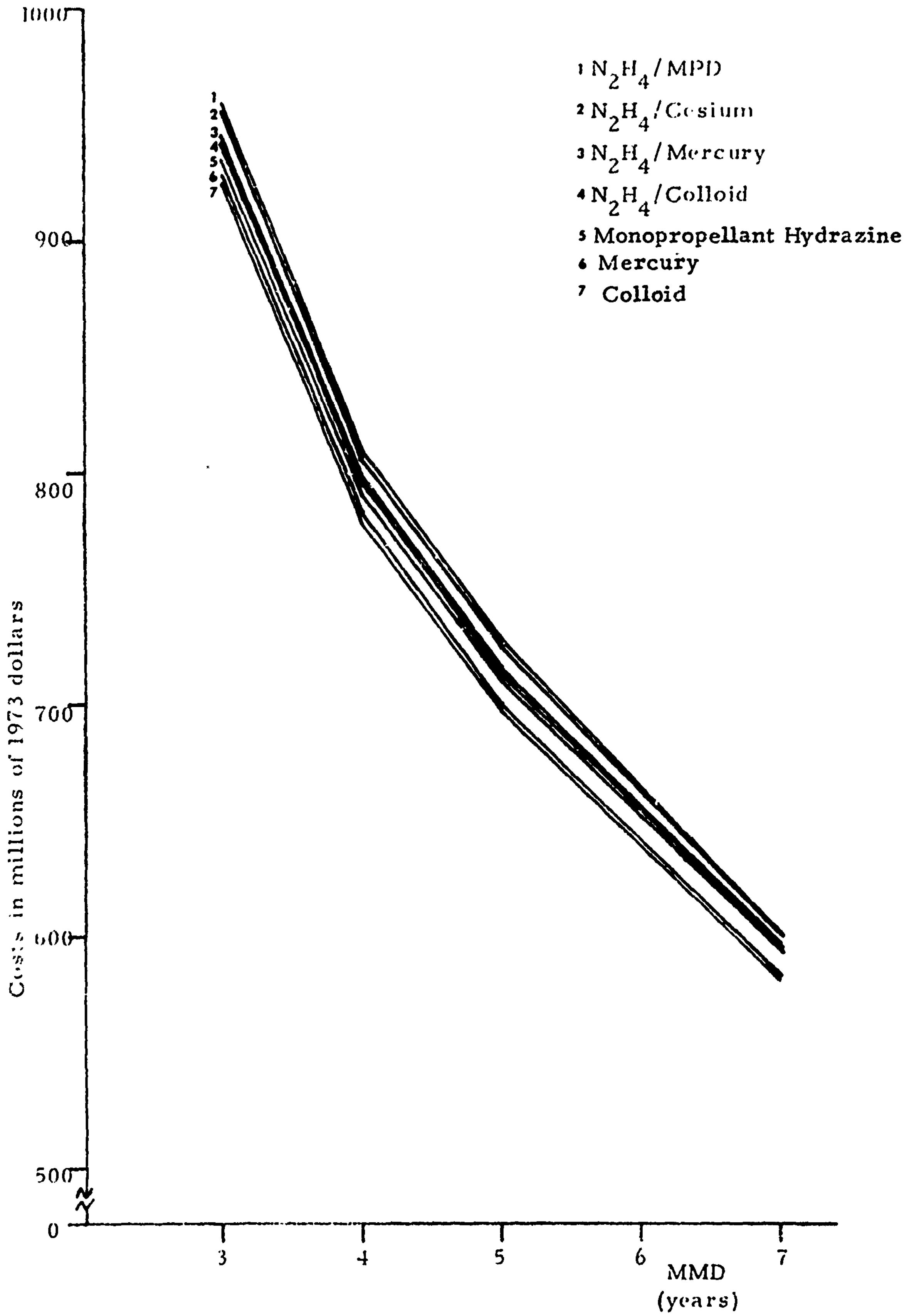


Fig. D3 Ten-Year System Cost of Constellation of Six Medium Category Satellites as a Function of the Mean Mission of the Satellite

(continued)

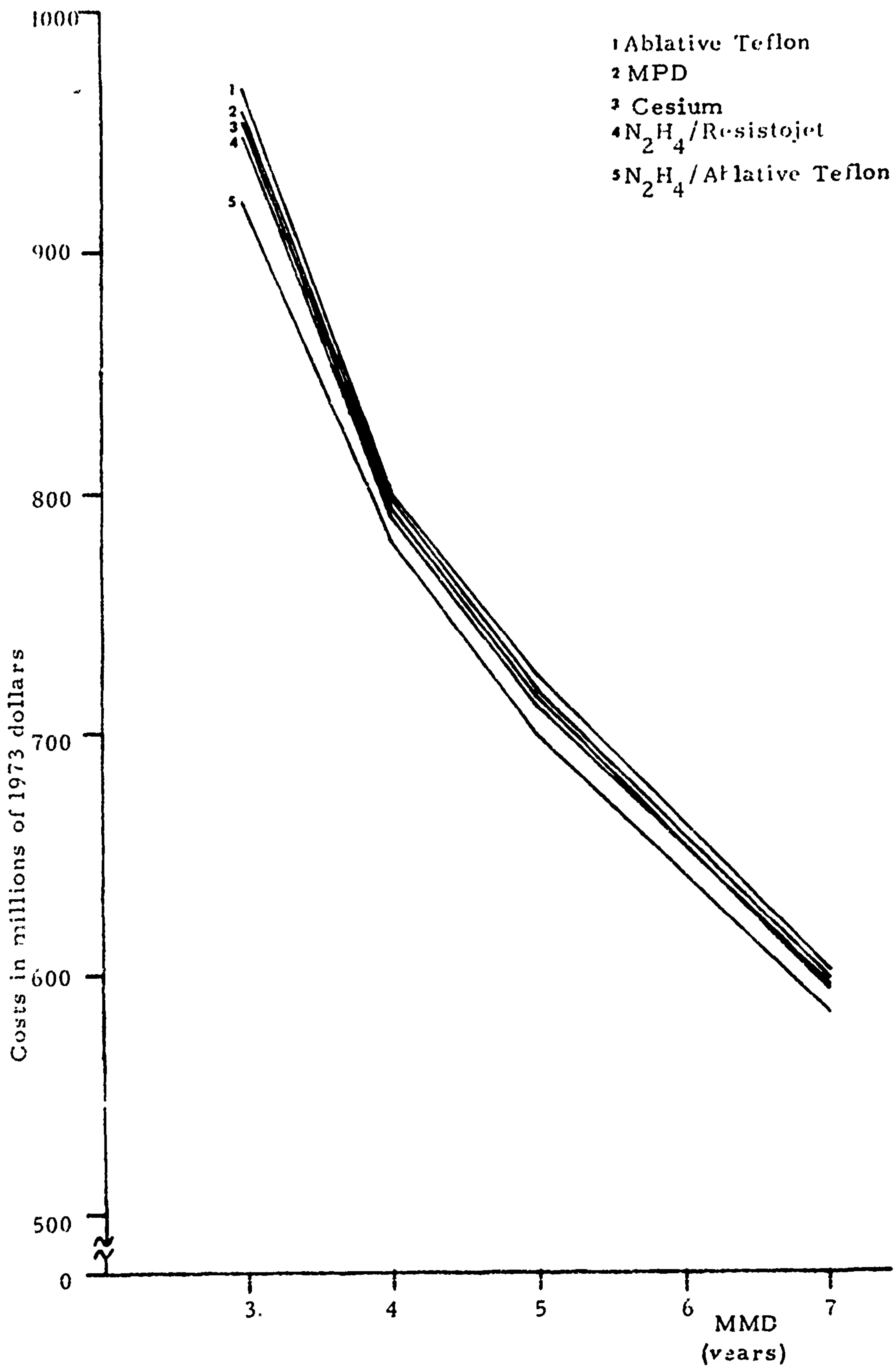


Fig. D3 (continued)

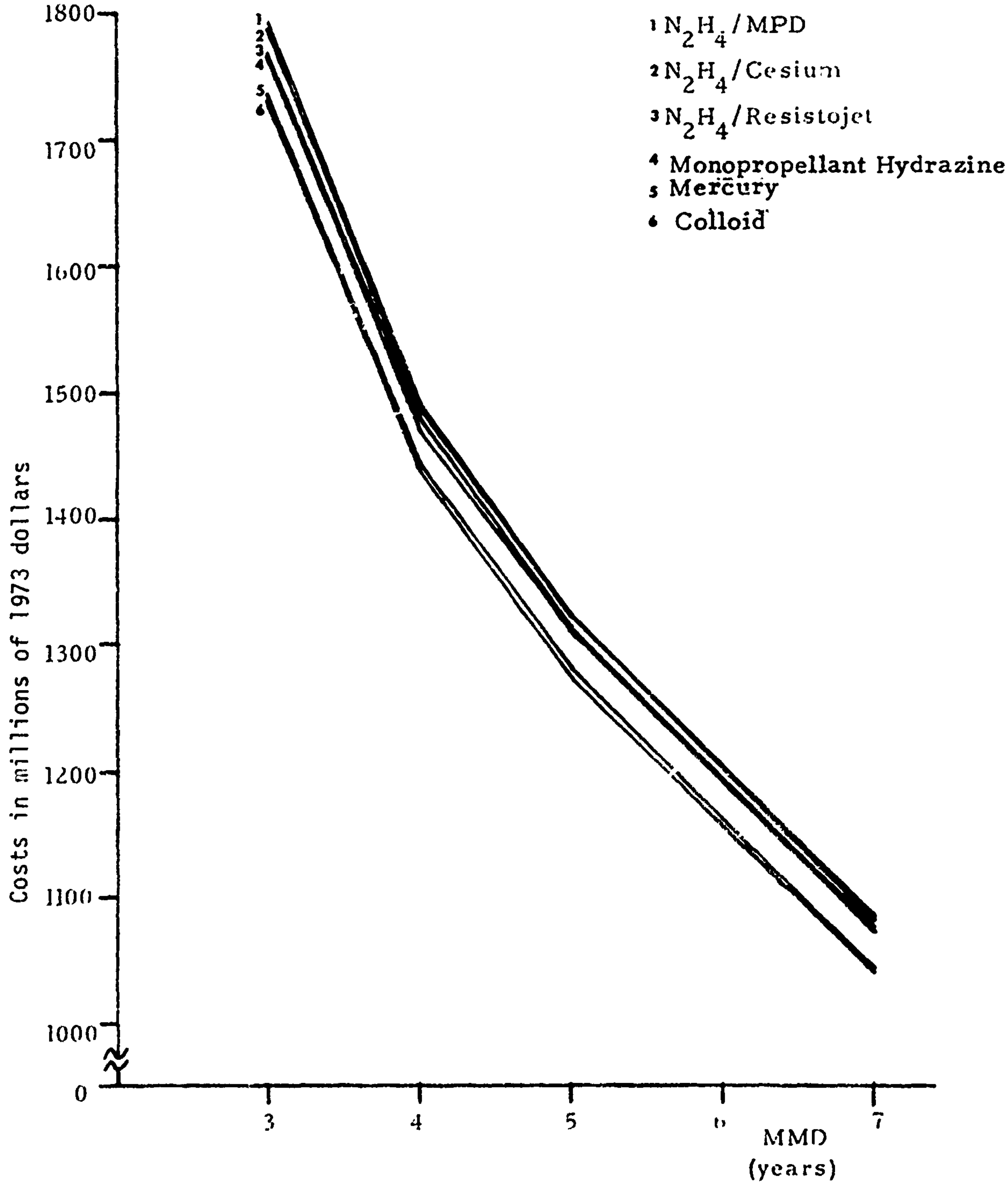
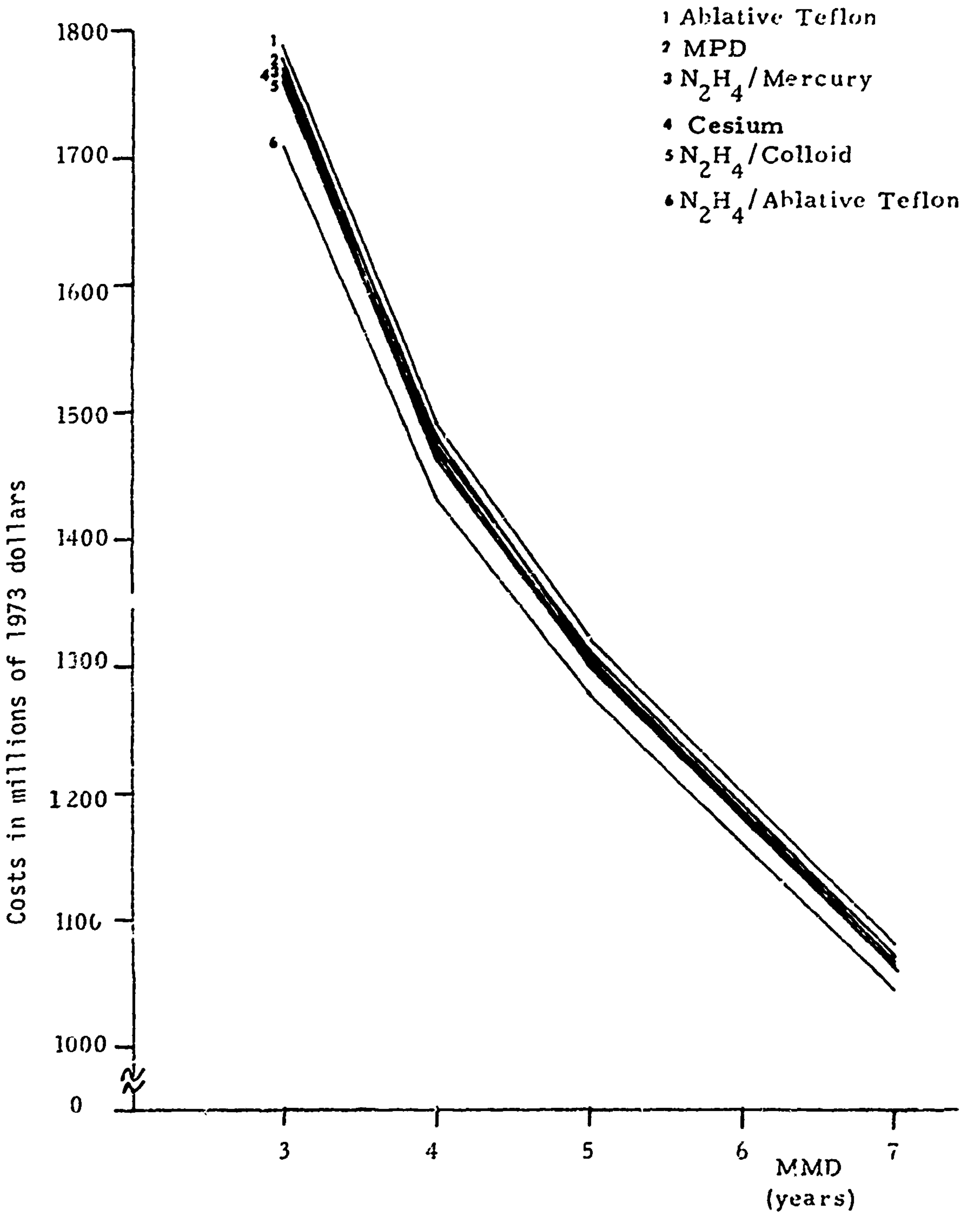


Fig. D4 Ten-Year System Cost of Constellation of Twelve Medium Category Satellites as a Function of the Mean Mission of the Satellite

(continued)



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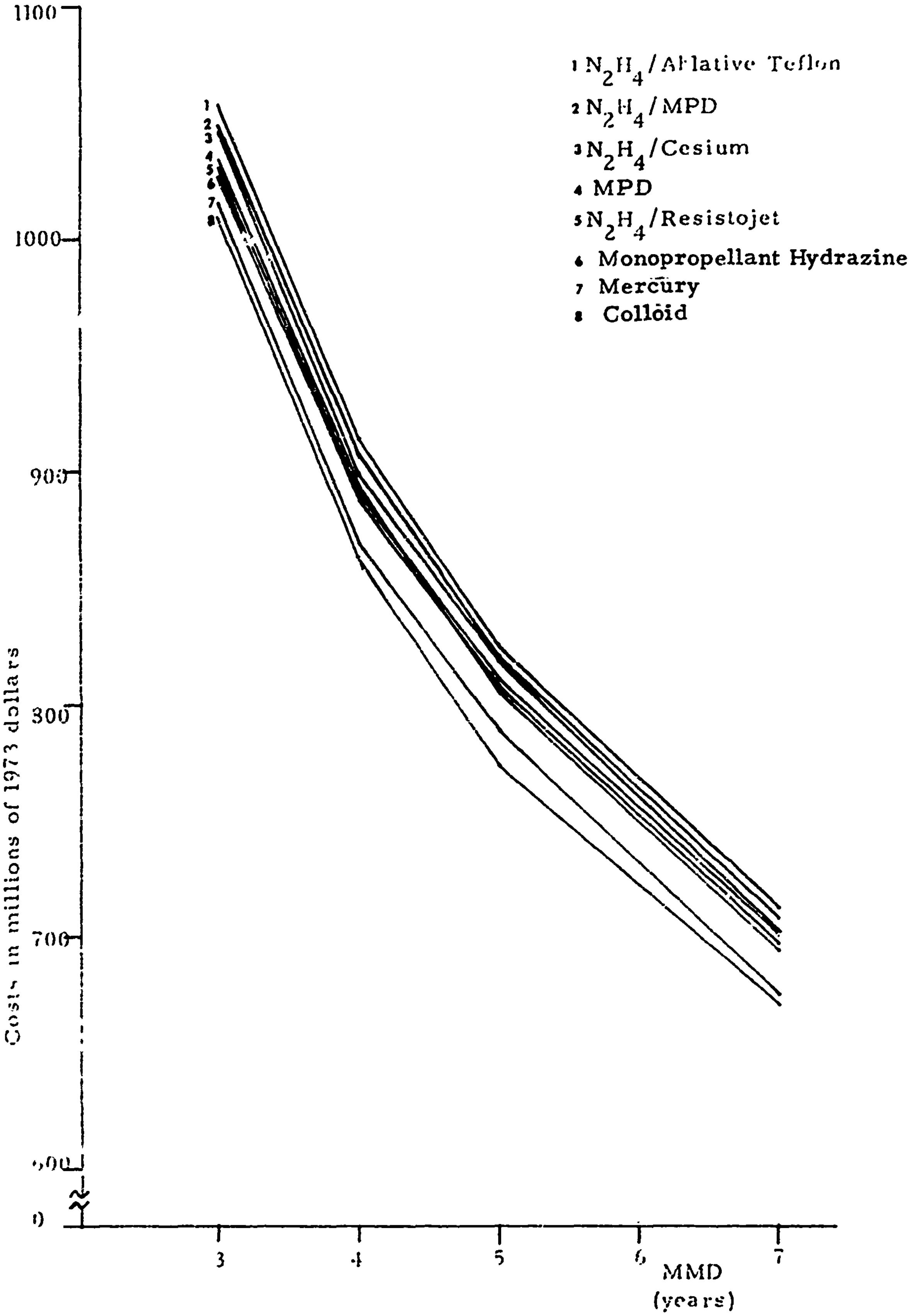

Fig. D5 Ten-Year System Cost of Constellation of Six Large Category Satellites as a Function of the Mean Mission of the Satellite

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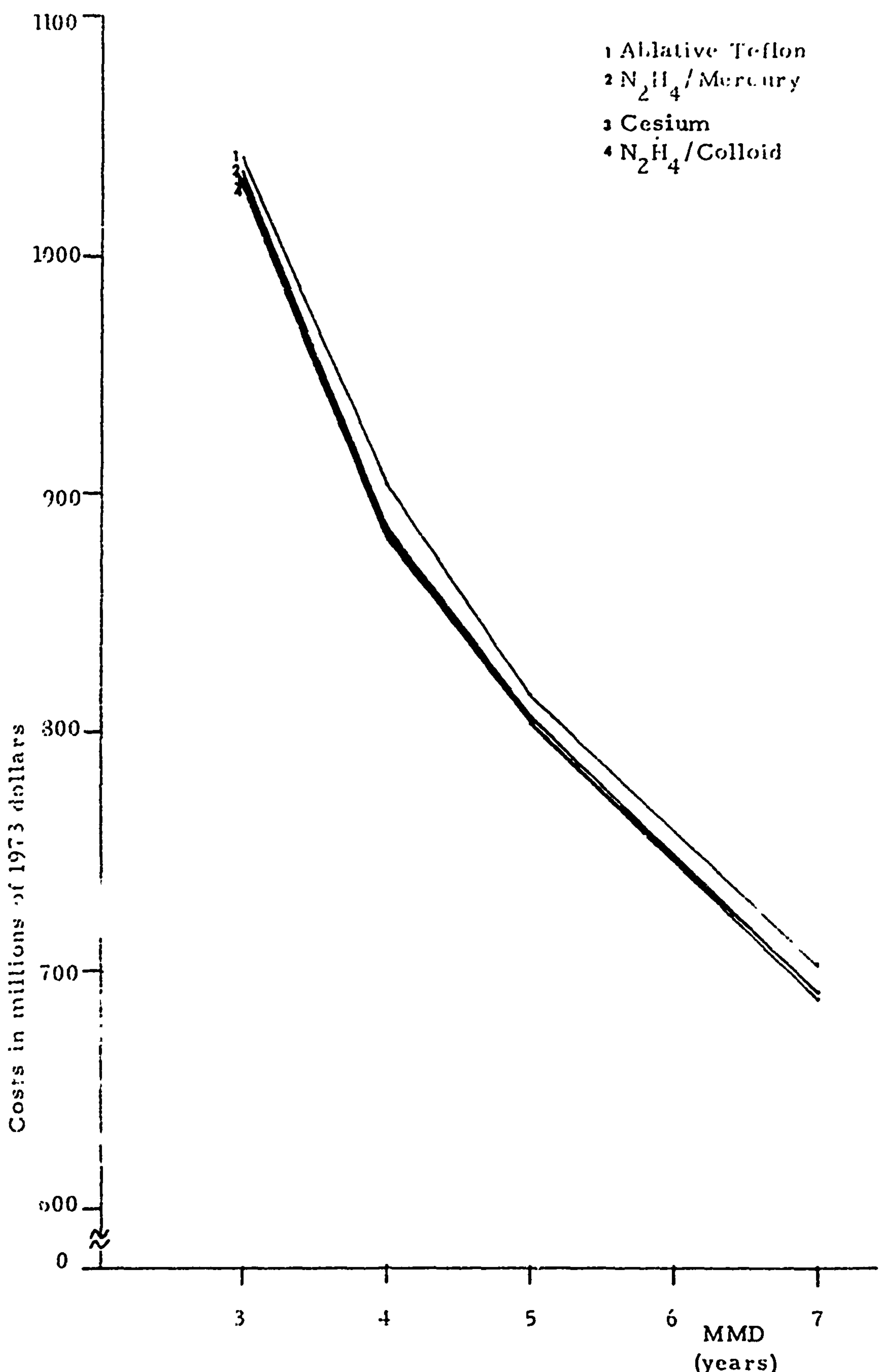

Fig. D5 (continued)

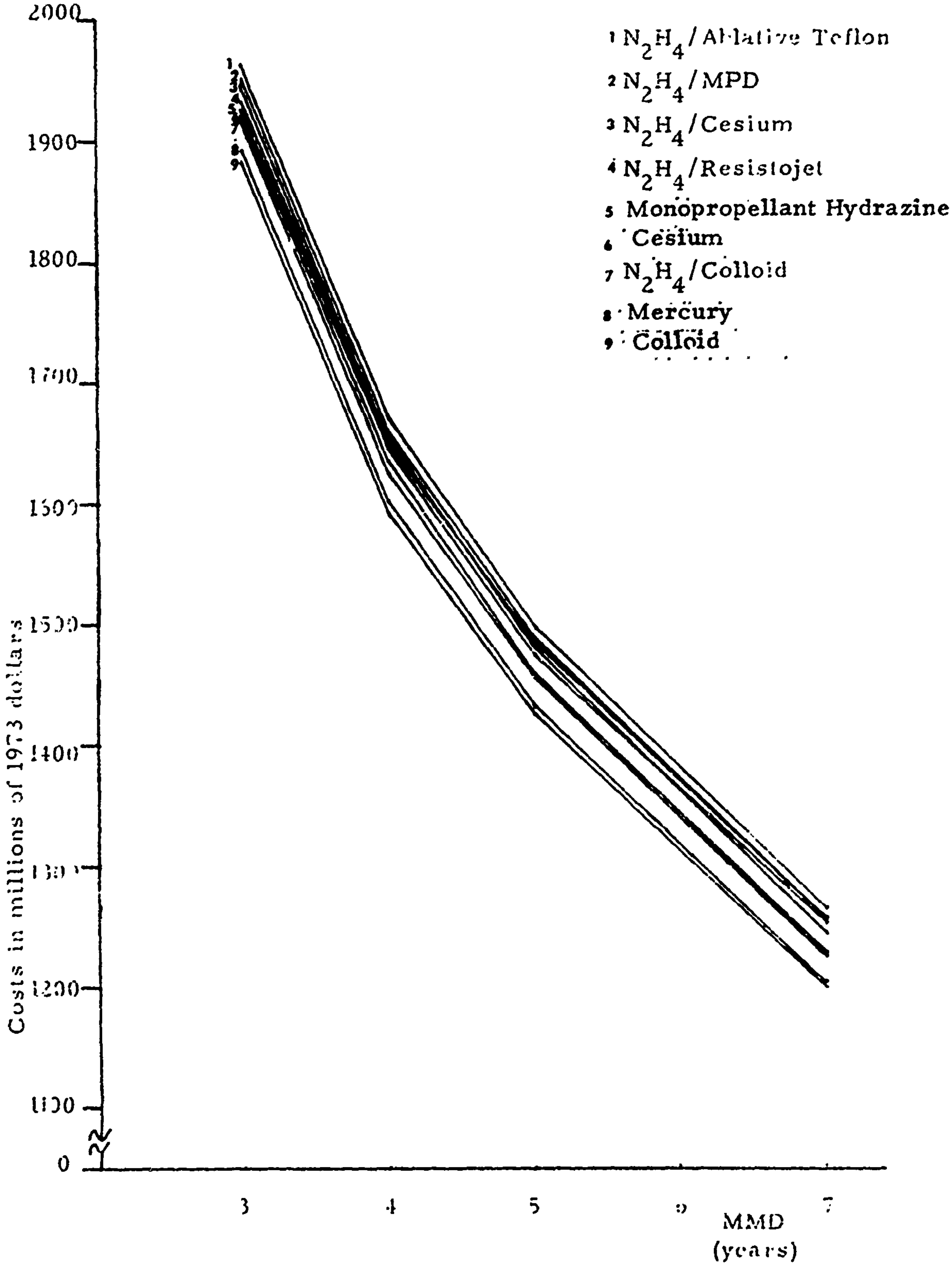

Fig. D6 Ten-Year System Cost of Constellation of Twelve Large ^ategory Satellites as a Function of the Mean Mission of the .. lite

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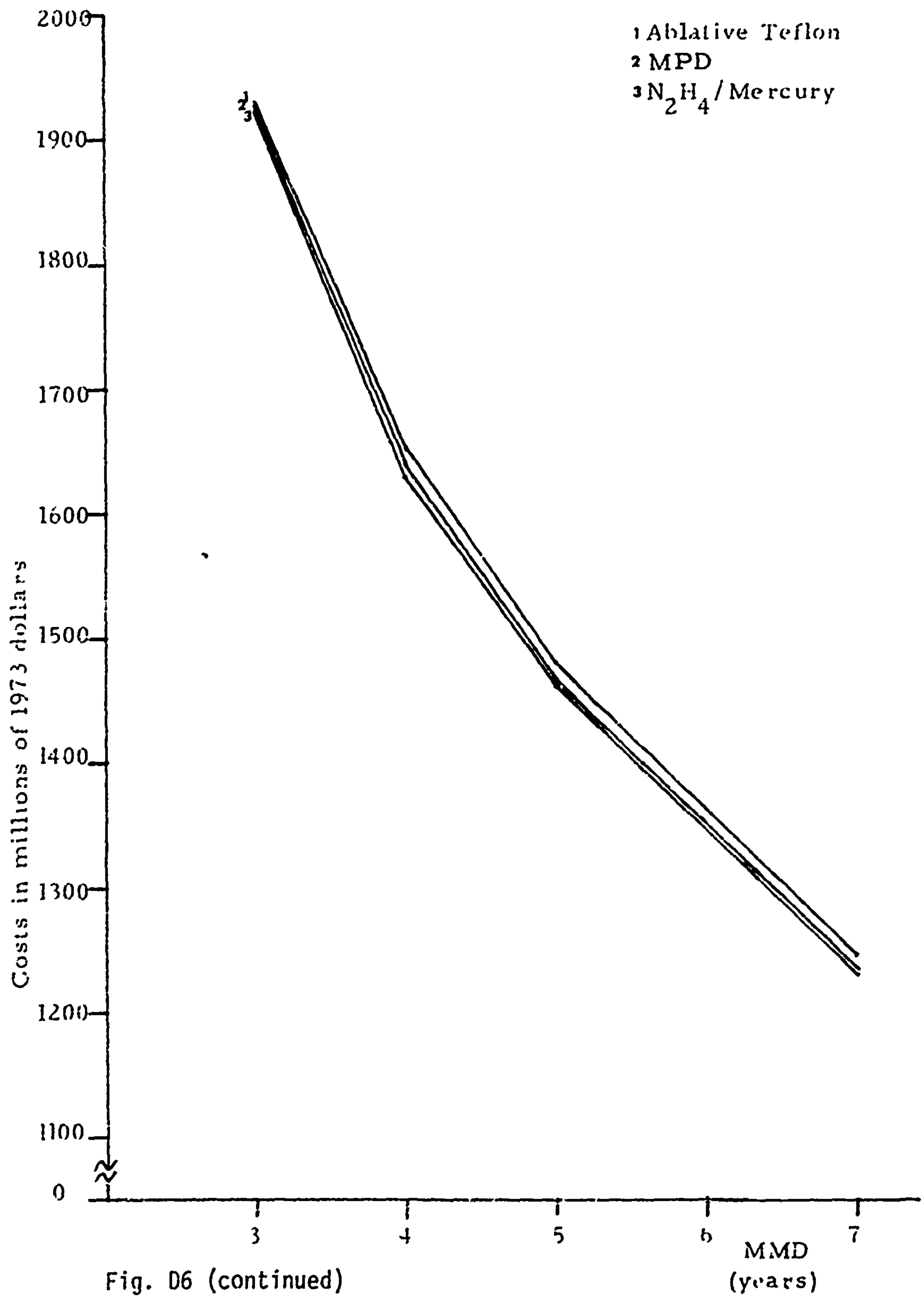

Fig. D6 (continued)